Deciphering climatic controls on sedimentation in a tectonically active area, Cyprus

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DECIPHERING CLIMATIC CONTROLS ON SEDIMENTATION IN A TECTONICALLY ACTIVE AREA, CYPRUS

Jennifer Victoria Waters

Abstract

The late Neogene to Quaternary of Cyprus is considered to be a tectonically active period coeval with major climatic change. Uplift, associated with the activities of the supra-subduction zone to south of island was concomitant with global cooling, the expansion of the Northern Hemisphere Ice Sheets and the Middle Pleistocene Transition. Despite the globally significant climatic events during the period of deposition, the Plio-Pleistocene climatic record in Cyprus is largely unknown and for the most part ignored. The objective of this study was therefore to investigate the stratigraphical record of the 'fore-arc', with the intention of elucidating the mechanisms controlling the cyclicity on sedimentation, in an attempt to understand the uplift history.

Sequence stratigraphical, palaeohydraulic, micropalaeontological and architectural analyses were conducted to provide an understanding of the sedimentary cyclicity, at key stratigraphical intervals. Correlation of the results to global patterns provided a robust method for deducing climatic controls on sedimentary deposition, thus leaving the residual record of tectonic uplift.

Cyprus is critically located in a region sensitive to climatic perturbations and is positioned between two major oscillatory atmospheric cells (Hadley and Ferrel Cells). The position of the boundaries of these cells is governed by the Inter Tropical Convergence Zone, which is controlled by latitudinal temperature gradients and ice volume. The effect of the Northern Hemisphere Ice Sheets and its influence on the climate belts over the eastern Mediterranean has been examined and has allowed the recognition of distinct climatic and oceanographic conditions.

The results indicate that the sedimentary evolution of the Cyprus 'fore-arc' responded to the progressive development of the Northern Hemisphere Ice Sheets and the orbitally controlled meridional movements of the Inter Tropical Convergence Zone. Tectonics created the relief and source necessary for deposition, whilst climate provided the overriding control on internal architecture within the depositional systems.

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Declaration

I declare that the work contained in this thesis was the result of my independent research, except where otherwise stated.

Signed ________________________

Jennifer Victoria Waters

February 2010

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Chapter 1

Introduction

The purpose of this study is to understand the uplift history of the Cyprus 'fore-arc' and to gain insight into the mode of uplift related to the activity of the supra-subduction zone to the south of Cyprus (Fig. 1.1). This was instigated to provide a test of current subduction models (Induced Nucleated Subduction Zone versus Spontaneously Nucleated Subduction Zone), since current perspectives on how subduction zones initiate and become self-sustaining still remains relatively unclear (e.g. Stern, 2004).

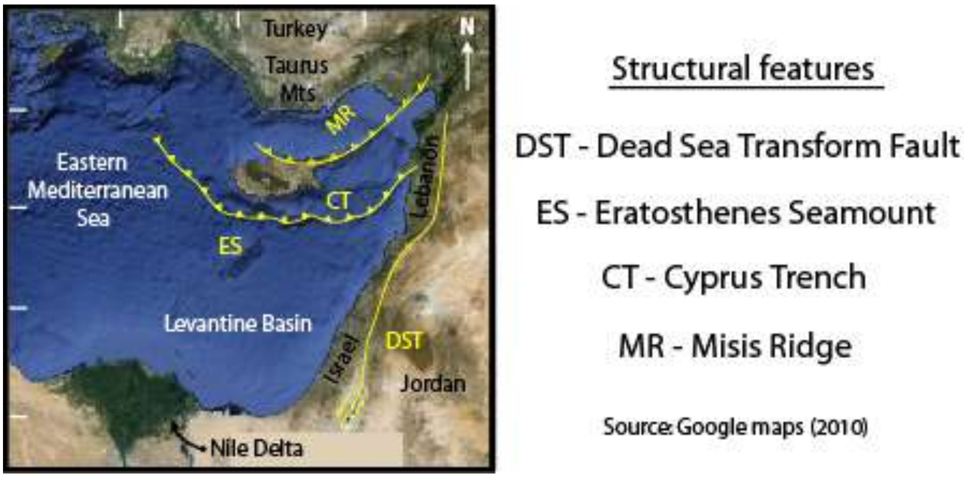


Figure 1.1 – Structural setting and positioning of Cyprus in the eastern Mediterranean Sea

Southern Cyprus was considered an ideal area for elucidating this information, primarily due to its status as a world class and rare example of an intact, relatively undeformed 'fore-arc' succession. It was envisioned that by de-convolving the climatic controls on sedimentation throughout the evolution of the 'fore-arc', that the residual record of tectonic uplift would be revealed. This could be achieved through employing techniques such as sequence stratigraphy, stable isotopic, palaeohydraulic, lithological, architectural and micropalaeontological analyses, with correlations to global climatic patterns.

The study focuses on the upper Neogene and Quaternary sedimentary deposits of the 'fore-arc' succession, a period considered to be tectonically active, although with a largely unknown and for the most part ignored climatic record. During this timeframe the sediments (predominantly siliciclastic) record a regressive sequence and a cyclical mode of deposition (e.g. Poole & Robertson, 1991), a sedimentary pattern that could have been influenced by tectonics and/or climate (including interrelated eustacy). If tectonism were an important control on sedimentary architecture, then it might be expected that Cyprus would be the place to see this. However, ongoing and lengthy debate exists on the relative roles of tectonics and climate on sedimentary sequences in tectonically active areas, particularly with respect to non-marine settings such as alluvial and fluvial deposits, due to 'a climatic ambiguity' of lithofacies (Miall, 1996). Differentiating between climatic and tectonic signatures and their respective influences upon sedimentation is challenging, as many researchers acknowledge (e.g. Ritter et al., 1995; Chough & Hwang, 1997; Frostick & Jones 2002; Hartley et al., 2005; Pope & Wilkinson, 2005; Shanley & McCabe, 1998).

A detailed review of the controls on sedimentation is beyond the scope of this introduction and is therefore only briefly outlined as follows. In general, tectonism is regarded to primarily influence sedimentation through the creation of accommodation and relief (Miall, 1996; Quigley et al., 2007), impacting upon the gradients and instability of systems, thus generating the potential for increased sediment flux (Frostick & Steel, 1993; Allen & Hovius, 1998; Jones, 2002; Dadson et al., 2004; Quigley et al., 2007). The cyclical sedimentation of clastic systems has therefore been extensively attributed to episodic tectonic movements (Frostick & Reid, 1989; Miall, 1996; Thamó-Bozsó et al., 2002). Although the role of tectonics on sedimentation is well-established, other processes such as glacio-eustatic sea level change, autocyclicity and climatically controlled sediment flux can produce similar depositional patterns (e.g. Dorsey et al., 1997; Overeem et al., 2001; Stouthamer & Berendsen, 2007; Massari et al., 2007; Kim & Jerolmack, 2008; Van Dijk et al., 2009) and are consequently frequently overlooked. For example, the association between sediment yield, precipitation (runoff) and vegetative stability is becoming increasingly recognised as a particularly important relationship (e.g. Langbein & Schumm, 1958; Frostick & Reid, 1989; De Boer et al., 1991; Jones, 2002; Pope & Wilkinson, 2005; Massari et al., 2007; Suresh et al., 2007; Jones & Frostick, 2008; Blechschmidt et al., 2009; Van Dijk et al., 2009).

It is critical to be able to distinguish between the influence of autocyclic (e.g. avulsion) and allocyclic (tectonics, climate and eustacy) processes to effectively elucidate the primary control(s) on the cyclicity within the 'fore-arc' deposits. This depends upon an understanding of the relative timescales of deposition that are involved. Tectonic processes tend to occur irregularly over large timescales and would not be correlatable to the predictable and regular patterns that would be characteristic of climatic Milankovitch scale cycles. Autocylic responses on the other hand operate locally (intrabasinal) and thus would not be recognisable on a basin wide scale, unlike extrabasinal tectonic, climatic or eustatic controls (e.g. Miall, 1996;Yang et al., 1998). Therefore by taking into account the above criteria, this research attempts to establish the allocyclic and/or autocyclic controls on the Upper Neogene and Quaternary basin fills of southern Cyprus. Key localities have been identified (Fig. 1.2) to help elucidate the relative controls and provide an understanding of the uplift history of Cyprus.

Figure 1.2 – Location of main study localities in northern and southern Cyprus

1.1 Geological context

The tectonic history discussed in the following section represents the understanding at the beginning of the study. The subsequent findings in this research will test the prior understanding.

1.1.1 Tectonic setting

Cyprus is the third largest island in the Mediterranean and the most easterly, located within the Levantine Basin, ~25 km to the north of the Cyprus supra-subduction zone, where the present day boundary between the converging African and Eurasian plates is located (Fig. 1.1).

The Troodos Massif, identifiable as an imposing feature across the centre of the island, is located on the hanging wall of the supra-subduction zone. It is composed of an oceanic crustal sequence, the highest point of which is denoted by Mount Olympus (1951 m a.p.s.l.). Uplift of the Massif is thought to have occurred in stages, gradually occurring from the late-Cretaceous to late-Oligocene followed by a more rapid phase during the late Miocene, in association with the initiation of the northwards dipping subduction zone (Orszag-Sperber et al., 1989; Poole & Robertson, 1991; Robertson et al., 1991; Stow et al., 1995; Schirmer, 2000; Davies, 2001). It is generally regarded that the most significant uplift occurred at the Plio-Pleistocene boundary, where focused uplift of the Troodos was coeval with emergence of the Kyrenia Range to the north (Robertson, 2000; Schattner, 2010). This phase has been related to the collision of the Eratosthenes Seamount (a continental fragment) with the Cyprus trench and was concomitant with serpentinite diapirism (Robertson, 2000). It is considered that uplift and extension has continued from the Plio-Pleistocene to the present day (Robertson, 1977; Poole et al., 1990; McCallum and Robertson, 1995), exemplified through a 'staircase' record of raised beaches. These deposits occur at heights of 100-110 m, 50-60 m, 8-11 m and <3 m suggesting uplift of the region was episodic (Poole et al., 1990; McCallum and Robertson, 1995) and indicating tectonically or climatically induced eustacy. Presently, only the western part of the island is considered active (Paphos area), whilst eastern Cyprus (Agia Napa area), is now thought to be virtually aseismic (Makris et al., 2000), indicating an eastward decrease in activity across the island.

1.1.2 Neogene to Recent geological context of Cyprus

The modern day configuration of the Mediterranean Sea was established in the early Miocene with the closure of the Levantine-Arabian connection (Rohling et al., 2009). Since the closure the only connecting point to the open sea is to the west through the Strait of Gibraltar, thus resulting in a semi-enclosed basinal arrangement, imposing significant impacts on oceanic circulation.

One of the consequences of the narrow connection to the open ocean (Atlantic Ocean) is revealed in the late Miocene geological record; where a thick sequence of evaporates denote a geologically momentous event in the history of the Mediterranean, known as the Messinian Salinity Crisis.

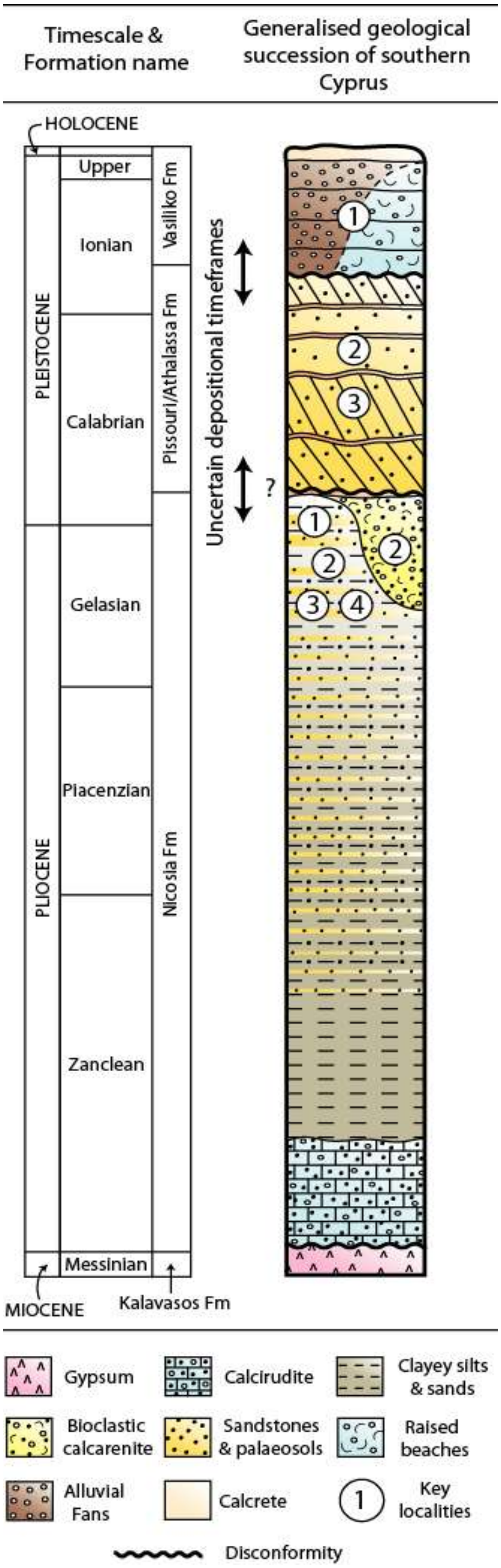


Figure 1.3 – Lithological column of southern Cyprus (late Miocene to Recent). Key localities are depicted on Fig. 1.2

It is believed this event was induced by the tectonic closure of the straits (Betic and/or Rifian straits, Krijgsman, 2002; Rohling et al., 2009), severing the connection between the Mediterranean Sea and the Atlantic Ocean. The subsequent tectonic opening of the Strait of Gibraltar in the early Pliocene (Rohling et al., 2009) and ensuing marine transgression (Lord et al., 2000; Rouchy et al., 2001; Soria et al., 2008) signifies the initiation of sedimentation pertinent to this study (marine, grey clayey silts). Since this event a general pattern of regression is recorded in the sedimentary succession of Cyprus, reflected in the transition from marine clayey silts through to fan delta deposits, eventually culminating in raised beaches and alluvial fans (Fig. 1.3). It is considered that ~2 km of uplift since the latest Pliocene to earliest Pleistocene (Eaton and Robertson, 1993; Stow et al., 1995; Schirmer, 2000; Davies, 2001), provided the relief and source necessary for the building of these clastic depositional systems.

These sediments have not been extensively investigated, the key texts that have been published include, Stow et al. (1995) and McCallum & Robertson (1995) for the fan deltas, Schirmer (2000) for the debrites and Bagnall (1960) and Poole & Robertson (1991, 2000) for the terraced raised beaches. Gomez (1987) documented alluvial terraces in southern Cyprus whilst the only prominent research on the alluvial fans is by Poole & Robertson (1998). Palaeontological studies have been carried out for the marine clayey silts e.g. Krashneninnikov & Kaleda (2005) and Houghton et al. (1990), whilst only a brief study on the lowermost deposits addresses the lithology (Orszag-Sperber & Rouchy, 2000). Generalized studies, which comprise the Upper Neogene to Quaternary, include Robertson (1977) and Lord et al. (2000).

1.2 An overview of the Mediterranean climate: Why was Cyprus the chosen study area?

The critical location of Cyprus within a semi-enclosed basin and positioning between two major oscillatory atmospheric cells (Fig. 1.4) makes the area inherently sensitive to the smallest of climatic perturbations (Casford et al., 2003; Marino et al., 2007; Rohling et al., 2009). Characteristically mild, wet winters and warm, dry summers (Giorgi & Lionello, 2008; Rohling et al., 2009) typify the Mediterranean climate today, influenced by the seasonal migrations of the Intertropical Convergence Zone (ITCZ) and associated climate belts. In the summer the northerly migration of the ITCZ brings the Mediterranean under a high-pressure regime, attributable to the descending portion of the northern Hadley Cell, thus leading to dry conditions, particularly over the southern Mediterranean (Fig. 1.4, Cramp & O'Sullivan, 1999; Giorgi & Lionello, 2008; Tzedakis et al., 2009). Conversely a southerly deflection allows moisture laden mid-latitude westerlies (associated with the Ferrel Cell) and winter cyclogenesis to be established (Cramp & O'Sullivan, 1999; Tzedakis et al., 2009).

Deviations from this modern day regime are evident within the Levantine Basin, where organic rich sediments termed 'sapropels' are found. These occur in discrete and regularly spaced bundles and are directly related to periods of enhanced freshwater flux (Rohling & Hilgen, 1991; Bar-Matthews et al., 2000; Kallel et al., 2000) during periods of strong summer insolation (compared to the present day, Rohling, 1994). Increased insolation promoted the development of Atlantic born Mediterranean depressions, which tracked eastwards towards Cyprus and enhanced rainfall during summer seasons (Fig. 1.4).

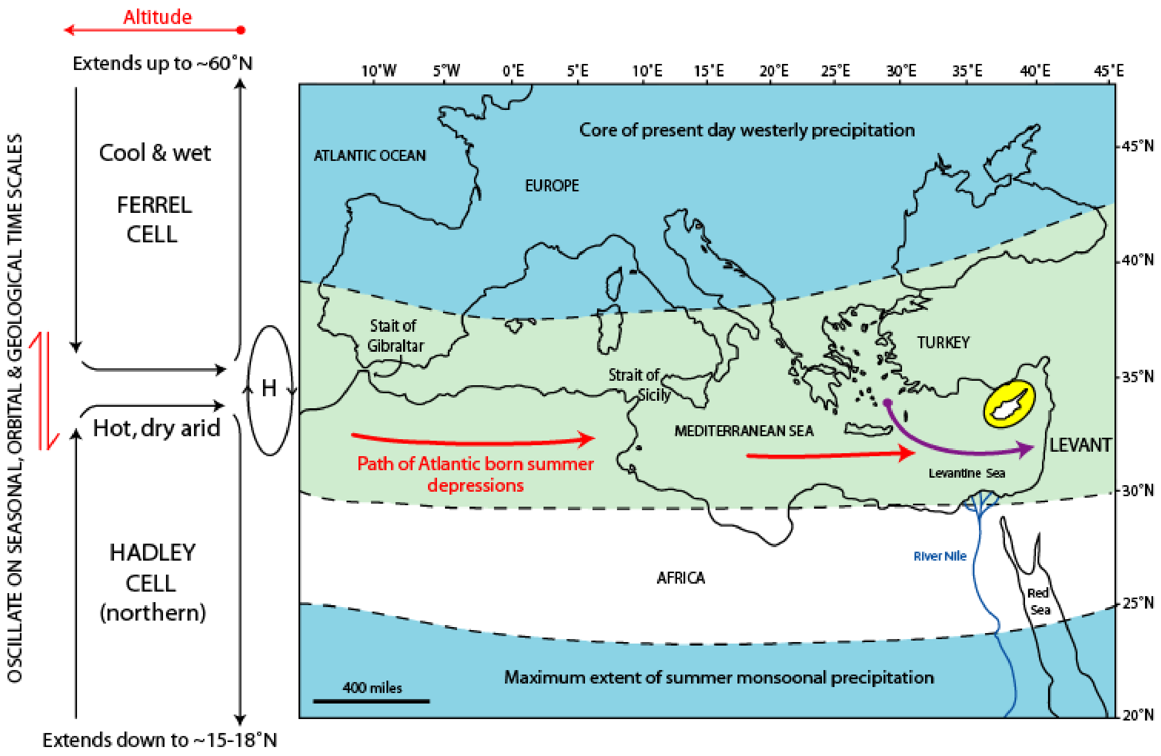


Figure 1.4 – Climatic systems influencing the eastern Mediterranean. Study area is highlighted in the yellow oval. H = high pressure. The lighter shade of blue denotes the outer zone of westerly precipitation and basinal winter cyclogenesis. Purple arrow represents approximate trajectory of anticyclonic winter rainfall (Cyprus low) based on Enzel et al. (2008)

This study focuses on the Pliocene to Recent deposits in Cyprus, a period during which dramatic, global climatic events occurred as the probable consequence of a downturn in atmospheric carbon dioxide concentrations (De Conto et al., 2008). This resulted in the expansion of the Northern Hemisphere Ice Sheets (NHIS) ~ 2.7 to 3.0 mya (Maslin et al., 1998; Willis et al., 1999; Marlow et al., 2000; Lisiecki & Raymo, 2007) and the Middle Pleistocene Transition (MPT) ~0.8 to 1.2 mya (e.g. Clark et al., 1999; Head & Gibbard, 2005). The Pliocene to Recent climates were therefore characterized by glacial (expansion) and interglacial (ablation) periods (e.g. Lambeck et al., 2002; Joannin et al., 2007), which had inevitable impacts upon the global eustatic sea level, oceanic circulation and latitudinal temperature (Fig. 1.5). Crucially, this affected thermally sensitive atmospheric phenomena such as the ITCZ, Hadley and Ferrel Cells, determining their intensity and meridional positioning (Rind, 1998; Lu et al., 2007; Armstrong et al., 2009).

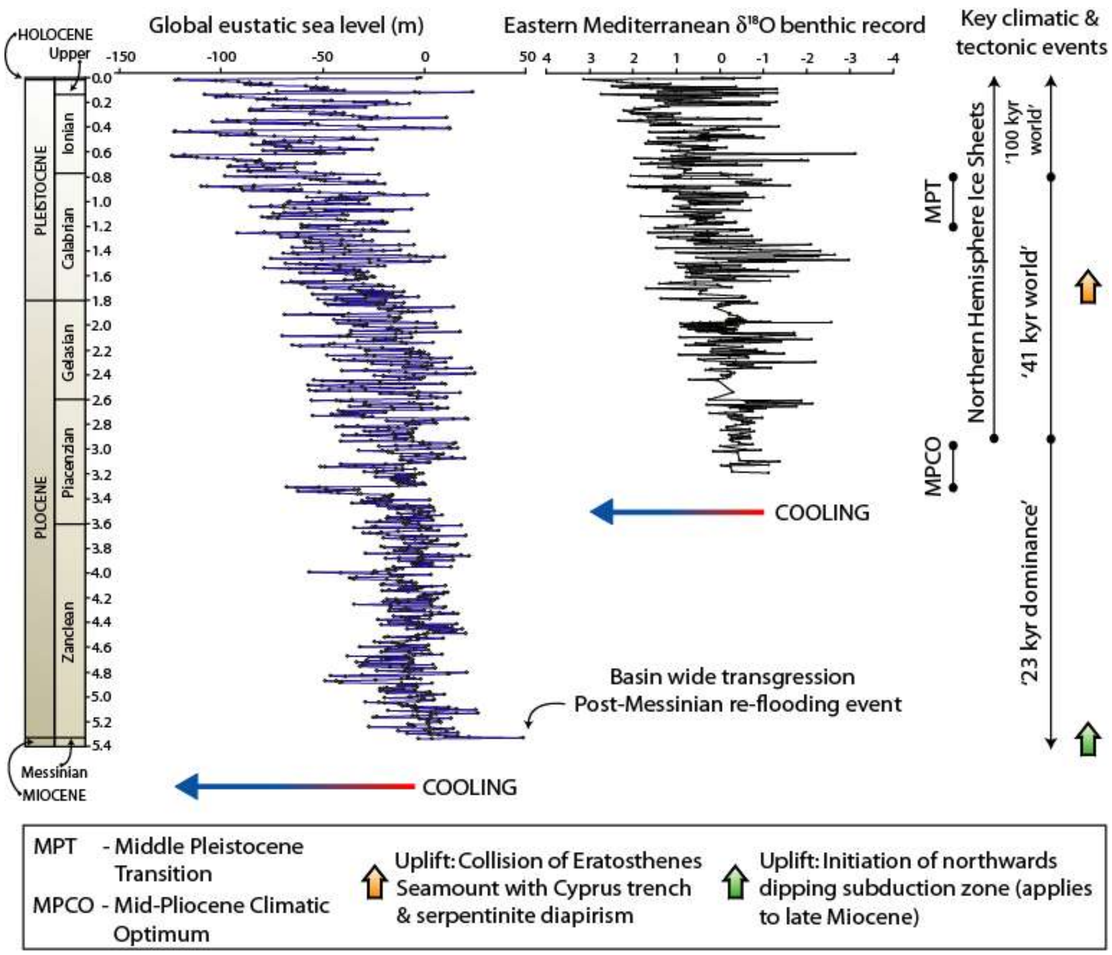


Figure 1.5 – Key climatic and tectonic events affecting the Mediterranean throughout the Upper Neogene and Quaternary. Global eustatic sea level curve from Miller et al. (2005), oxygen isotope record from Kroon et al. (1998)

It has long been established that the NHIS have waxed and waned with the same periodicities as the Earth's orbital parameters of eccentricity (~100 and 400 kyr), obliquity (~41 kyr) and precession (~19-23 kyr). Changes in the configuration of these astronomical forces have driven global climate change throughout the Neogene and Quaternary (Pillans et al., 1998; Clark et al., 1999), primarily controlling the seasonal and latitudinal distribution of solar insolation (Clark et al., 1999; Rind, 2002).

Prior to the permanency of the NHIS the Mediterranean responded to low latitudinal precessional variations, reflected in a continuous sapropel chronology (Van Vugt et al., 1998; Tzedakis, 2007). However, with the expansion of the NHIS, climate became sensitised to high latitude insolation changes, reflected as obliquity scale glacial-interglacial variability (a linear response to orbital forcing), until a critical ice sheet threshold was attained at the MPT. Ice sheets began to respond non-linearly to orbital forcing complicated by the interaction of internal feedback mechanisms such as CO_2 and albedo (Clark et al., 1999; Maslin & Ridgwell, 2005). Thereafter, 100 kyr (short) eccentricity became the dominant orbital parameter, modulating the amplitude envelope of precession (e.g. Maslin & Ridgwell, 2005).

Numerous studies across the Mediterranean postulate a climatic control on cyclical alternations in marine and terrestrial successions, invoking a linkage with the changeable variations in the Earth's orbital parameters (e.g. Postma et al., 1993; Weltje & De Boer, (1993); Kroon et al., (1998); Van Vugt et al., (1998); Wehausen & Brumsack, (1999); Foucault & Mélières (2000); Lourens et al., (2001); Joannin et al., 2007; amongst others). These studies implemented a multitude of techniques including mineralogical, geochemical and computational approaches, faunal and floral analyses and correlations of high-resolution chronostratigraphy to astronomically forced cyclicity. The sediments of Cyprus should therefore provide a relatively intact archive of past climatic variability, likely to be recognisable on orbital timescales, as an abundance of literature for the surrounding area suggests. This theory is tested using a primarily sedimentological and micropalaeontological approach using sedimentary structures, faunal assemblage variations and palaeohydraulics to understand changes in climatic conditions.

1.3 Problem identification and hypothesis formulation

The key problem approached in this study is to decipher to what extent climate influenced the depositional cyclicity throughout the evolution of the Cyprus 'fore-arc'. Once this has been deduced the record of tectonic uplift should be evident. As previously indicated the Plio-Pleistocene is regarded to be a tectonically active period and sedimentary cyclicity is frequently attributed to tectonic movements. However, the climate record in Cyprus, during this period, is largely unknown and for the most part ignored. From the discussion above it is clear that globally significant climatic events occurred during the Plio-Pleistocene, reflected as predictable frequencies in sedimentary successions across the Mediterranean (in a variety of tectonic settings). Despite this no climatic controls have been convincingly identified in the Cypriot sedimentary successions of comparable age. This may perhaps be the result of over emphasis on the role of tectonics. Furthermore, the lack of chronostratigraphic control made connections with cyclical climatic perturbations problematical and inference rather than detailed attempts at understanding the cyclicity were made.

The location of Cyprus between two major oscillatory atmospheric cells (each carrying a characteristic climatic signature, section 1.2) and the climatic sensitivity of the eastern Mediterranean should be signatures evident in the sedimentary record of the ‘forearc’ succession. It may perhaps be expected that key periods will be dominated by specific climatic modes leading to the following hypotheses:

Hypothesis 1: Upper Neogene to Quaternary sedimentary cyclicity in Cyprus occurred on orbital periodicities, providing climate was the overriding control on sedimentary architecture.

This hypothesis leads to a set of predictions, listed below. Each prediction is addressed in separate chapters of this thesis and will be discussed shortly.

Prediction 1: Obliquity scale cyclicity (~ 41 kyr) will be expressed in the stratigraphical record of the mid Pliocene to early Pleistocene succession, directly related to glacial-interglacial variations of the NHIS.

Prediction 2: During the mid Pleistocene to late Pleistocene short eccentricity (~100 kyr) will control sedimentary cyclicity as a consequence of the MPT. Lowstand deposits will dominate sedimentary sequences, the result of rapid deglaciations and long-lived glacial build-ups.

Prediction 3: Sedimentary cyclicity in the late Pleistocene to Recent successions will reveal precessional variations (~ 23 kyr), strongly modulated by short eccentricity.

The second hypothesis is related to Hypothesis 1, continuing with the theory that climate is controlling the internal sedimentary architecture of the successions.

Hypothesis 2: Oscillations in the positioning of the Hadley and Ferrel atmospheric cells, and their distinctive climatic characteristics, will be evident within the climatically sensitive eastern Mediterranean marine and terrestrial environments.

Prediction: Wetter and drier and/or cooler and warmer periods will be reflected on an orbital cyclicity within foraminiferal assemblages and facies changes.

The final and key hypothesis is addressed in Chapter 5 and is proposed as follows:

Hypothesis 3: During the Upper Neogene and Quaternary tectonics provided the relief and source necessary for sedimentation, whilst climate was the overriding control on sedimentary architecture.

Prediction: Sedimentary evolution of the Cyprus 'fore-arc' will record the progressive and climatic variations of the NHIS and MPT. This will be reflected through an overall lowering of sea level and distinctive orbitally controlled, cool, warm, wet and dry periods.

These hypotheses are tested in key stratigraphical intervals represented by the chapters of this thesis; each chapter progresses in chronostratigraphical order and are discussed below. The main test of the hypotheses lies in the correlation of the deposits to the known Plio-Pleistocene climatic record. If no correlation is evident a tectonic driver may be implied.

Chapter 2: Eastern Mediterranean foraminiferal palaeocological responses to Plio-Pleistocene climate change

The marine, grey, clayey silts of the Nicosia Formation could be the product of the transgressive re-flooding event; post the Messinian Salinity Crisis (e.g. Houghton et al., 1991) or perhaps a much earlier Miocene age (e.g. Schirmer, 2000). In this study, the identification of age diagnostic foraminifera, in the uppermost part of the formation suggests a maximum late Pliocene to early Pleistocene age (1.8-2.1 mya, *Globorotalia inflata* and *Globigerina cariacoensis* biozones; Iaccarino, 1989), thus conforming to the post Messinian re-flooding hypothesis. It was envisioned that the lithological cyclicity and abundance of foraminifera within the formation could be used to provide an understanding of the climatic controls on deposition. The recognition of age diagnostic foraminifera provided an accurate timeframe for the correlation of lithological cycles to the global eustatic sea level curve and $\delta^{18}O$ record, thereby testing Hypothesis 1

(Prediction 1). The identification of foraminiferal assemblages diagnostic of specific ecological and hence climatic conditions was used to reconstruct ocean-climate interactions in the eastern Mediterranean, testing both Hypothesis 1 and 2.

Chapter 3: Sedimentary evolution of a braided fan delta complex (Pissouri Basin, Southern Cyprus) during Pleistocene sea level change

The Pissouri Basin in southern Cyprus exhibits a shallowing upward succession in the hanging wall of the Cyprus supra-subduction zone, where a progression from shallow marine silts to fluvio-deltaic sandstones culminate in raised beach and alluvial fan deposits. Previous studies have hypothesized tectonism to be the dominant control on the depositional architecture of the fan delta succession (e.g. Stow et al., 1995), however it is notable that the deposits are coeval with a phase of major climatic change, coincident with the MPT (chronostratigraphical constraints indicate deposition between ~1.8 and ~0.42 mya). In order to be able to establish the controls on relative sea level, detailed interpretation of the facies and sequence stratigraphical analysis was required. The identified parasequences are systematically correlated with the global eustatic sea level curve and Mediterranean wide successions, in an attempt to understand the main controls on the depositional architecture, a process which tests Hypothesis 1 (Prediction 2) and to some extent Hypothesis 2.

Chapter 4: Climatic controls on late Pleistocene alluvial fans, Cyprus

Previous work on the alluvial fans (fanglomerates) across Cyprus suggests the deposits are predominantly the product of tectonic activity (especially the older fans; Poole & Robertson, 1998), in accord with the traditional view of the primary control on alluvial fans, where climate is frequently neglected (e.g. Frostick & Reid, 1989; Allen & Densmore, 2000; Densmore et al., 2007). Tentative assertions have been proposed suggesting: i) (humid) climate may have played a modifying role on the sedimentary architecture of the fans (Poole & Robertson, 1998) and ii) the fans may be the product of heavy pluvials that occurred during the Pleistocene ice ages (Bagnall, 1960; Houghton et al., 1990). However, no detailed studies on the internal cyclicity within these deposits have been undertaken to resolve such theories. This study approaches this issue through the palaeohydraulic reconstruction and architectural analysis of the deposits, with the aim of understanding the controls on the abrupt cyclical alternations in the facies, in view of testing Hypothesis 1 (Prediction 3). It is hypothesized that patterns of increasing and decreasing palaeoflow dynamics are reflected in the facies changes, with coarser deposits symptomatic of wetter conditions and finer deposits indicative of drier modes (testing Hypothesis 2).

Chapter 5: Deciphering climatic controls on sedimentation in a tectonically active area, Cyprus

This chapter collates the evidence from the preceding chapters and places the findings into the broader context, thus testing Hypothesis 3. The tectonic and climatic controls on the basin fills throughout the Upper Neogene and Quaternary evolution of the Cyprus 'fore-arc' are evaluated and the original aim of the study is re-addressed, based upon the findings in the research.

Chapter 2

Eastern Mediterranean foraminiferal palaeoecological responses to Plio-Pleistocene climate change

Abstract

Age diagnostic planktonic foraminifera from the upper Nicosia Formation, Cyprus yield a maximum late Pliocene to early Pleistocene age (1.8-2.1 mya, *Globorotalia inflata* and *Globigerina cariacoensis* biozones). Deposition of the formation is therefore coincident with the re-flooding of the eastern Mediterranean following the Messinian evaporate crisis and concomitant with the expansion of the Northern Hemisphere Ice Sheets (a consequence of atmospheric downturn in CO_2). The grey clayey silts of the Nicosia Formation exhibit a lithological cyclicity and contain an abundance of foraminifera, thus leading to the hypothesis that sedimentary cyclicity and foraminiferal palaeoecology can be used to reconstruct the ocean-climate interactions in the eastern Mediterranean**.**

The hypothesis is tested through the correlation of the sedimentary cyclicity to the global eustatic sea level curve where an orbital control on the deposits is indicated. Furthermore, foraminiferal palaeoecological analysis has allowed the recognition of two specific ocean-climate states; i) cool subtropical, dominantly eutrophic oceanographic conditions, influenced by minor runoff to the north of the Troodos Massif and greater runoff to the south and, ii) warm subtropical, oligo-eutrophic oceanographic conditions under the influence of high runoff.

Cyprus is positioned between two major oscillatory atmospheric cells (low latitude Hadley Cell and mid-high latitude Ferrel Cell) and should consequently be an ideal location for deducing perturbations in the palaeoclimate. It is therefore proposed that the lithological cyclicity and changing foraminiferal ecology is consistent with orbitally induced shifts in the latitudinal location of the atmospheric cells and associated climate belts. Cool subtropical conditions indicate the dominance of the mid-latitude westerlies of the Ferrel Cell, whilst warm subtropical conditions are reflective of Hadley Cell dominance.

2.1 Introduction

The grey clays of the Nicosia Formation across Cyprus represent a significant shift towards deeper water facies, when compared to the underlying Kalavasos Formation. The Nicosia Formation provides the basement to and maximum age control of the overlying poorly fossiliferous fan delta complex of the Pissouri Formation (Chapter 3).

The deposits in the vicinity of Khirokitia and the Amala Mountains area (southern Cyprus; Fig. 2.1) have previously been attributed an early-middle Miocene age (Schirmer, 2000). This was based upon regional mapping and lithostratigraphical relationships using, i) the presence of overlying gypsum, mapped as the Kalavasos Formation (late Miocene, Messinian age) and, ii) apparently grey clays lying topographically beneath limestones containing the age diagnostic foraminifera *Discospirina* (late Miocene). Schirmer therefore places the grey clays within the Pakhna Formation, consequently pre-dating the early Pliocene re-flooding of the Mediterranean following the Messinian Salinity Crisis. However gypsum bearing deposits occur in the Pleistocene-Holocene of southern Cyprus and the *Discospirina* limestones lie in faulted contact with the grey clays, therefore these criteria cannot provide an age constraint. Alternative hypotheses indicate the basal grey clays are early Pliocene in age (Di Stefano et al., 1999; Orszag-Sperber & Rouchy, 2000, Rouchy et al., 2001), where Stow et al., (1995) and Orszag-Sperber & Rouchy. (2000) compared the basal deposits of the Pissouri area to the white and blue “Trubi” marls of Sicily. Krasheninnikov & Kaleda (2005) verify this through foraminiferal biozonal evidence, where the Zanclean *Sphaeroidinellopsis* zone (Mediterranean specific) was identified. Furthermore, studies on the uppermost Nicosia Formation indicate a late Pliocene to early Pleistocene age. For example, Houghton et al. (1990) recorded *Discoaster triradiatus* (NN17-NN18; 1.85-2.35 mya) an age assignment consistent with unpublished palaeomagnetic data of Kinnaird (2008) and foraminiferal identification of Davies (2001). Davies (2001) reported *Globigerina cariacoensis* from the grey clays just beneath the alluvial fans in Vasiliko Quarry (~9 km to the southwest of Khirokitia), indicating an early Pleistocene age (~1.8 mya). In this study the presence of the Plio-Pleistocene planktonic foraminiferal biozones *G. inflata* and *G. cariacoensis* (NN21-NN22, 1.8-2.1 ma), within the upper part of the Nicosia Formation, is confirmed. The top of the grey clays can therefore be considered part of the post Messinian succession, conforming to the re-flooding hypothesis.

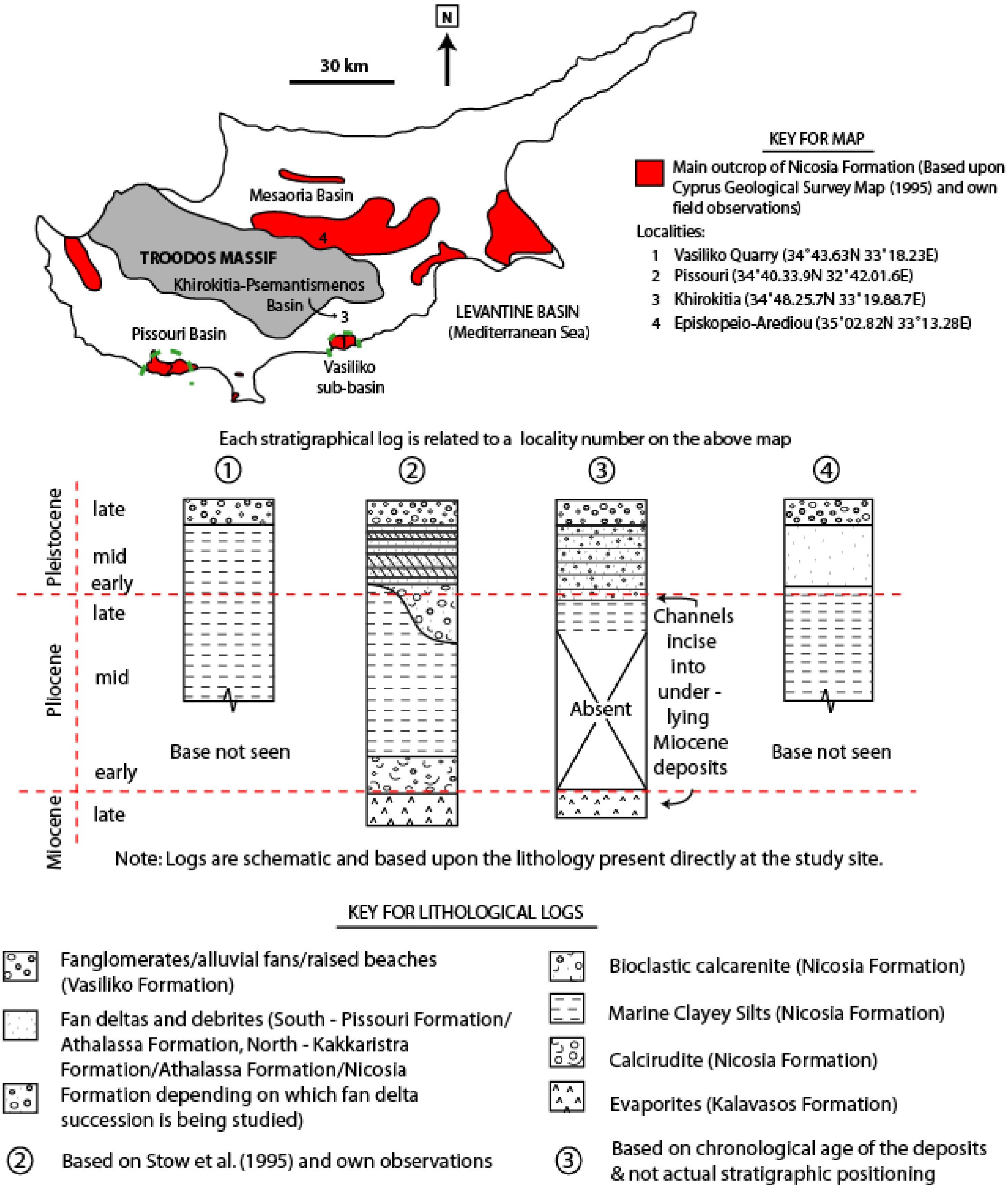


Figure 2.1 – Study localities, distribution of the Nicosia Formation and stratigraphical context of the relevant basins

The grey clay succession spans a critical interval coincident with a major period of climatic cooling and significant growth of the Northern Hemisphere Ice Sheets (Zachariasse et al., 1989; Maslin et al., 1998; Willis et al., 1999; Lambeck et al., 2002; Miller et al., 2005; Lisiecki & Raymo, 2007; Clark et al., 2008). It is widely recognised long-term cooling began in the early late Pliocene ~ 2.7 to 3.0 mya (Maslin et al., 1998;

Lambeck et al., 2002; Capozzi & Picotti, 2003; Ravelo et al., 2004; Billups, 2005; Raymo et al., 2006), coincident with a downturn in atmospheric CO_2 (Pearson & Palmer, 2000; DeConto et al., 2008), a fall in relative sea level of ~ 45 m and coeval with a globally progressive enrichment of $\delta^{18}O$ in benthic foraminifera (Fig. 2.2, Raymo et al., 1992). The general growth and decay of the ice sheets and the associated relative sea level changes were partially controlled by the interaction of periodic climatic variations, which determined the timing of glacial episodes and intensified the effects of the NHIS (Maslin et al., 1998; Willis et al., 1999; Marlow et al., 2000; Miller et al., 2005). These variations were related to incoming solar radiation, waxing and waning with the same regular periodicities of the orbital parameters of eccentricity, obliquity and precession (Clark et al., 1999). It is generally accepted that obliquity predominantly affects higher latitudes and changes in ice volume, whilst precession is related directly to insolation, exerting a control on mid to low latitudes, with a particular influence on monsoonal intensity (Kroon et al., 1998; Raymo et al., 2006; Tzedakis, 2007). It is considered that between 2.6 and ~0.8 mya obliquity was the dominant orbital parameter (Pillans et al., 1998; Roveri & Taviani, 2003; Raymo et al., 2006); thereafter precession, modulated by (short) eccentricity became the principal control (Lourens & Hilgen, 1997; Rohling & Thunell, 1999; van Vugt et al., 2001; Head & Gibbard, 2005; Lisiecki & Raymo, 2007). From a Mediterranean perspective, climate change from the Miocene until the onset of the NHIS was fundamentally controlled by precession. At this critical turning point, obliquity became superimposed on the precession signature (deMenocal, 1995; Tzedakis, 2007), becoming the dominant controlling mechanism throughout the mid Pliocene to mid Pleistocene (particularly strong between 1.9-1.0 mya; Kroon et al., 1998).

The mid- to low- latitude positioning of Cyprus within the eastern Mediterranean places the island between high latitude obliquity and mid to low latitude precessional influence. Climatic conditions are regulated by two major atmospheric cells, which oscillate meridionally across the Mediterranean. Presently, the Hadley Cell promotes warm to hot summers, although deviations from the present day (warm and wet summers) are documented and are explained in the following section. The Ferrel Cell and mid latitude westerlies, on the other hand, bring cool to mild, wet winters across the region (Cramp & O’Sullivan, 1999; Giorgi & Lionello, 2008; Fisher et al., 2009; Rohling et al., 2009; Tzedakis et al., 2009). This climatic regime may have been

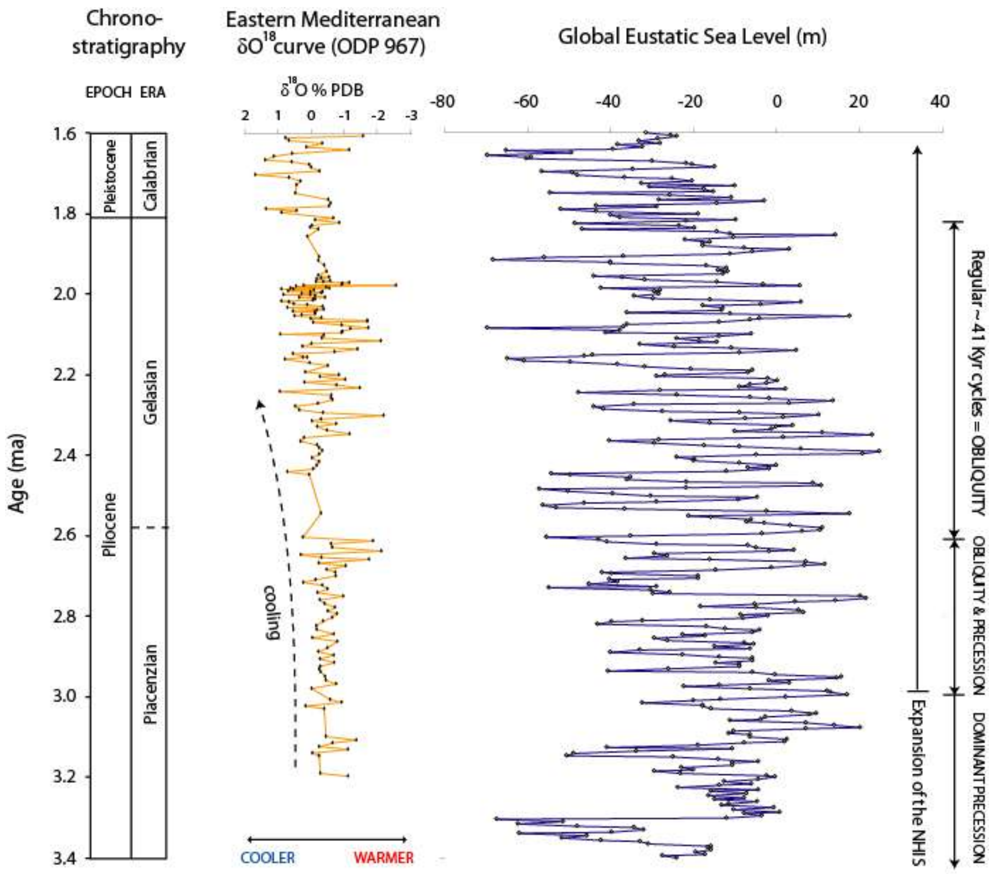


Figure 2.2 – Trends within the global eustatic sea level curve and benthonic oxygen isotope record for the mid Pliocene to early Pleistocene (representative timeframe of the mid to upper Nicosia Formation grey clayey silts). Oxygen isotope record from Kroon et al. (1998), eustatic sea level curve from Miller et al. (2005).

initiated by the expansion of NHIS (Suc, 1984). Cyprus therefore provides an ideal area for examining climatic perturbations in these phenomena. The marine record documents these responses particularly well due to the climatic sensitivity of the Mediterranean Sea (explained below). It is therefore envisaged that any such climatic responses would affect the hydrography of the Mediterranean (i.e. changes to the thermohaline circulation, ocean stratification and ventilation) and will be identifiable in the pelagic and benthic microfauna of the Nicosia Formation.

2.1.1. Pliocene to Recent circulation and foraminiferal ecological record of the Mediterranean Sea

At the present day the semi-enclosed Mediterranean Sea is connected to the Atlantic Ocean at the narrow Strait of Gibraltar, and is strongly influenced by North Atlantic climatic changes (see Rohling et al., 2009 for an overview). The Mediterranean Sea exhibits a unique anti-estuarine or inverse water circulation (Astraldi et al., 1999; Cramp & O'Sullivan, 1999; Krijgsman, 2002; Monaco & Peruzzi, 2002), which results in the sea acting as a concentration basin (Béthoux & Pierre, 1999). It is not clear when the anti-estuarine circulation became a permanent feature; one view is this initiated in the late Miocene (Kouwenhoven & Van der Zwaan, 2006), whilst a second suggests it has been present since the Pleistocene and possibly as early as the Pliocene (Hayward et al., 2009).

Currently the Mediterranean Sea is characterized by temperate warm conditions, even at depth temperatures fall no lower than 11°C (Cimerman & Langer, 1991). The basin is considered to be distinctly oligotrophic i.e. a food limited environment with low nutrient content and well oxygenated conditions (Murray, 1991; Crise et al., 1999; Duarte et al., 1999; Turley, 1999; Schmiedel et al., 2003). This oligotrophy increases eastwards with the most oligotrophic conditions evident within the Levantine Basin (Azov, 1991; Zohary & Robarts, 1992; Turley, 1999; Abu-Zied et al., 2008; Hayward et al., 2009). The nutrient poor conditions are attributed to the current deficit of freshwater runoff into the basin (Duarte et al., 1999). During the summer, oligotrophic conditions prevail in the eastern Mediterranean, typified by the high abundance of the planktonic foraminifera *G. ruber* (constituting ~80% of the assemblage, Pujol & Vergnaud-Grazzini, 1995), whilst in the winter, there is a presence of eutrophic species such as *G. bulloides*.

Studies of benthic foraminifera have successfully demonstrated that the Mediterranean Sea (with particular reference to the eastern basin) is extremely sensitive to climatic forcing and responds rapidly to abrupt climatic changes compared to the open ocean (Crise et al., 1999; Turley, 1999; Casford et al., 2003; Schmiedel et al., 2003; Marino et al., 2007). The semi-isolated nature of the basin from the open ocean contributes to these rapid and amplified responses (Rohling et al., 2004). For example, it has been documented that a drop in temperature can result in the onset of deep-water formation and subsequent ventilation of the mid-low latitude, semi-enclosed, small volume deep basins of the Mediterranean (Casford et al., 2003; Schmiedel et al., 2003; Stefanelli et al., 2005). Conversely, strong climatic warming often induces water column stratification and an associated decline in oxygen in deep bottom waters (Kroon et al., 1998; Emeis et al., 2003; Pérez-Folgado et al., 2003; Stefanelli et al., 2005). An example of such a climatic regime is clearly demonstrated as basin-wide events across the whole of the Mediterranean Sea where black, organic rich deposits termed 'sapropels' were deposited. These are particularly well developed in the Levantine Basin (eastern Mediterranean) and have been an intermittent feature from the Miocene up to the Holocene. Sapropels develop in response to minima in the precession index (Rohling & Hilgen, 1991; Kroon et al., 1998; Bar-Matthews et al., 2003; Capozzi & Negri, 2009) and are associated with wetter and generally warmer periods (i.e. summer; Bar-Matthews et al., 2000; Kallel et al., 2000) and have been connected with increased activity of Mediterranean depressions (Rohling & Hilgen, 1991). The resulting increase in freshwater flux into the Levantine Basin enhanced nutrient content within the water column, promoted marine surface productivity and water column stratification. The consequent flux of organic matter to deeper water and decomposition of detritus reduced the oxic content of the bottom waters (e.g. Rohling & Hilgen, 1991; Nijenhuis & de Lange, 2000), instigating sluggish deep-water circulation and the development of eutrophic conditions.

Foraminifera are sensitive indicators of seafloor and water column ecology and therefore provide important archives of climate and ocean state interactions. Planktonic species in particular are sensitive to sea surface temperature, the degree of water column stratification and nutrient availability (Kucera, 2007; Pujol & Vergnaud Grazzini, 1995). Benthic foraminifera are similarly regulated by food availability (nutrient content), however demonstrate greater sensitivity to organic flux (Van der Zwaan et al., 1999; Stefanelli et al., 2005) and are consequently particularly excellent indicators of bottom water oxygenation (Seidenkrantz et al., 2000).

Given the introduction above it is predicted lithological cyclicity in the Nicosia Formation will record obliquity scale variations, whilst changes in foraminiferal ecology will reflect the orbital variations in atmospheric cells. An initial hypothesis, using the modern day climatic conditions as analogy, would predict that warm, dry conditions would be reflected through a dominantly oligotrophic foraminiferal assemblage, whilst cool, wet periods would favour the proliferation of eutrophic species. If warm, wet conditions prevailed it may be expected that both a mixture of oligotrophic and eutrophic species will be present.

2.2 Methodology

Data has been collected systematically through logged sections of the Nicosia Formation, from both north (Episkopeio-Arediou) and south (Vasiliko Quarry) of the Troodos Massif (Fig. 2.1). Sampling was focussed in the upper 2.5 m at Episkopeio-Arediou and upper 5 m at Vasiliko Quarry; the samples were taken at 0.5 m and 1 m intervals respectively. Reconnaissance samples were taken at Pissouri (~ 5 m below the contact) and Khirokitia (~ 2.5 m, 10.5 m and 11.5 m below the contact) with the primary aim of confirming the age of the deposits.

Samples were processed for foraminifera using standard separation techniques. Boiling water was sufficient to disaggregate the grey clays and foraminifera were picked and identified from the 125 μm size fraction. The sample was split into fractions, 1/8th, 1/16th or 1/32th depending on sample size. A minimum of 300 complete specimens were collected and identified and photographs were taken using an SEM (Hitachi TM-1000 Tabletop). Identification of foraminifera was based upon key texts such as Kennett & Srinivasan (1983), Loeblich & Tappen (1988), Bolli et al. (1989), Hemleben et al. (1989) and Cimerman & Langer (1991). Abundances were normalised to number of specimens per gram of rock and identified species were expressed as percentages (%) of the total number of planktonic (benthonic) foraminifera (Appendix A & B). Foraminifera species with abundances ≥2% in at least one sample were considered representative enough for assessing palaeoecological trends (Becker et al., 2005; Drinia et al., 2005; Drinia et al., 2008). Specific assemblages were identified and are defined through the grouping of ecologically similar species (≥ 2%) and fluctuations in their abundance, presence and absence (Tables 2.1 & 2.2). Appendix A exhibits all of the species identified in this analysis. First Appearance Datums (FAD) were used to give the maximum possible age and minimize errors associated with reworking. These were compared to published Mediterranean biozonal schemes (Iaccarino, 1989).

Diversity indices were calculated using PAST (version 1.91; Hammer et al., 2001). The indices for each sample have been measured using the following parameters, i) ***Fisher -alpha index***, this provides the relationship between the number of species and the number of individuals in each sample (Fisher et al., 1943; Drinia et al., 2005; Murray, 2006), ii) ***Equitability*** or ***Evenness***, measures how the species are evenly distributed among the other species within a sample (Buzas & Gibson, 1969). High equitability (approaching 1) indicates a nearly equal distribution of species in a sample,

		Stratigraphical level below the contact (m)				
		2.5	2.0	1.5	1.0	0.5
PLANKTONIC	*G. bulloides*	7.56	14.73	6.50	6.87	8.41
	G. inflata	0.00	0.00	0.00	6.87	6.55
	G. sacculifer	0.00	0.00	3.25	0.00	11.21
	O. universa	5.66	0.00	0.00	6.87	8.41
	G. ruber	54.73	20.94	21.14	34.37	28.97
	G. tenellus	11.32	14.73	21.95	13.12	0.00
	G. rubescens	3.78	17.83	22.76	19.37	13.08
	G. glutinata	7.56	10.85	8.95	3.13	4.67
	G. siphonifera	0.00	3.87	4.87	0.00	6.55
BENTHONIC	*C.pachydermus*	3.04	6.29	15.99	18.22	11.65
	U. mediterranea	0.00	0.00	0.00	5.91	0.00
	N. labradoricum	0.00	0.00	0.00	3.45	2.46
	G. umbonata	7.58	3.78	2.85	5.41	0.00
	M. barleeanus	4.55	3.15	2.85	3.94	2.46
	G. affinis	4.55	2.52	3.43	3.94	2.46
	A. parkinsona	9.09	0.00	6.29	5.91	0.00
	V. bradyana	6.08	5.04	8.00	5.41	4.29
	C. carinata	4.55	2.52	5.72	2.96	6.74
	G. orbicularis	6.08	2.52	5.72	3.94	4.29
	B.exilis	7.58	0.00	2.85	2.46	3.68
	B.spathulata	3.04	2.52	2.28	3.45	4.90
	A. mamilla	0.00	3.15	4.57	0.00	11.65
	H. boueana	0.00	6.29	2.28	0.00	2.46
	T. saggitula	0.00	3.78	2.85	0.00	3.68
	S. bulloides	3.04	5.04	0.00	0.00	2.46
	R.rotundiformis	0.00	2.52	0.00	0.00	0.00

Table 2.1 – Foraminifera in Episkopeio-Arediou with abundances ≥2% in at least one sample. Note: only foraminifera with ecologically well-known habitat characteristics were considered in this analysis

low equitability (approaching zero) indicates the dominance of one particular species in the faunal assemblage, iii) ***Dominance***, has a converse relationship with equitability. Low dominance (high equitability) indicates no species domination whereas high dominance (low equitability) is indicative of an assemblage dominated by a few specific species, iv) ***Shannon Index*** is dependent on the number of species and the number of individuals (of each species) in the sample. Rare species of low abundance will contribute little to the value of this index (Abu-Zied, 2001) and v) ***Planktonic: Benthonic*** (P:B) ratio is often regarded as a crude bathymetric indicator, nevertheless it was used to provide an indication of potential depth variations and calculated using the method of Van Der Zwaan et al. (1990). In general terms lower diversity and higher

		Stratigraphical level below the contact (m)				
		5.0	4.0	3.0	2.0	1.0
PLANKTONIC	*G. bulloides*	9.71	57.51	37.49	33.30	20.00
	G. inflata	0.00	2.50	0.00	14.81	10.00
	G. sacculifer	5.83	2.50	16.68	25.93	20.00
	O. universa	6.80	32.51	12.50	11.11	0.00
BENTHONIC	*B. aculeata*	6.02	4.55	8.59	25.69	14.58
	E. bradyi	2.41	0.00	4.30	3.67	4.17
	G. affinis	0.00	5.68	2.46	0.00	0.00
	G. lamarckiana	8.43	10.23	6.14	4.59	0.00
	N. terquemi	25.30	4.55	15.95	15.60	18.75
	H. balthica	0.00	5.68	3.07	0.00	5.21
	B. spathulata	13.66	9.09	22.09	15.60	7.29
	M. barleeanus	3.21	10.23	3.68	8.26	3.12
	U. mediterranea	2.81	6.82	2.46	3.67	3.12
	B. striata	2.01	2.27	0.00	0.00	2.08
	R. spinulosa	5.62	0.00	0.00	2.75	3.12
	Q. limbata	0.00	2.27	0.00	2.75	4.17

Table 2.2 – Foraminifera in Vasiliko Quarry with abundances ≥2% in at least one sample. Note: only foraminifera with ecologically well-known habitat characteristics were included in this analysis

dominance is often representative of either a shallow shelfal area or restricted, perhaps stressed and unfavourable environmental conditions (Drinia et al., 2005; Kouwenhoven, 2000).

The predictions are tested by correlation of the lithological cyclicity and changing foraminiferal ecology to the global eustatic sea level, oxygen isotope curve and insolation parameters.

2.3 Geological setting, biostratigraphical and lithostratigraphical framework of the Pliocene to early Pleistocene in Cyprus

The Pissouri, Vasiliko and Khirokitia-Psemantismenos Basins in southern Cyprus and the Mesaoria Basin in central Cyprus (north of the Troodos Massif) contain a relatively thick succession (minimum of ~70 m) of rhythmically bedded marls. These deposits, which are placed in the Nicosia Formation unconformably overlie the Kalavasos Formation (Fig. 2.1), which comprises shallow marine carbonates and evaporites attributed to the Messinian Salinity Crisis of the late Miocene (Bertoni & Cartwright, 2007; Robertson et al., 1991; Foucault & Mélières, 2000, Soria et al., 2008; Spezzaferri

& Tamburini, 2007). This facies change has been mapped extensively within the Mediterranean and has been interpreted to be the result of a major transgression following the Messinian Salinity Crisis (e.g. Lord et al., 2000; Rouchy et al., 2001; Soria et al., 2008) and provides the basis of this study.

2.3.1 Age determination of the Nicosia Formation

Figure 2.3 shows the stratigraphical ranges of the eponymous Mediterranean biozonal species identified: *Globorotalia inflata* (1.8-2.1 mya to Recent) and the representative biozone fossil for the Plio-Pleistocene boundary, *Globigerina cariacoensis* (1.8 mya to Recent, Iaccarino, 1989). *G. inflata* first occurs at 4 m below the top of the Nicosia Formation at Vasiliko Quarry and at 1 m at Episkopeio-Arediou (Fig. 2.3, Table 2.1 & 2.2). *G. cariacoensis* was only identified at Vasiliko Quarry, first appearing 3 m below the top of the formation (Fig. 2.3, Appendix A, Table A.3). *Globigerinoides tenellus* is also present and is considered age diagnostic for the Plio-Pleistocene (Kennett & Srinivasan, 1983; Iaccarino, 1989), but has not been used to define biozones.

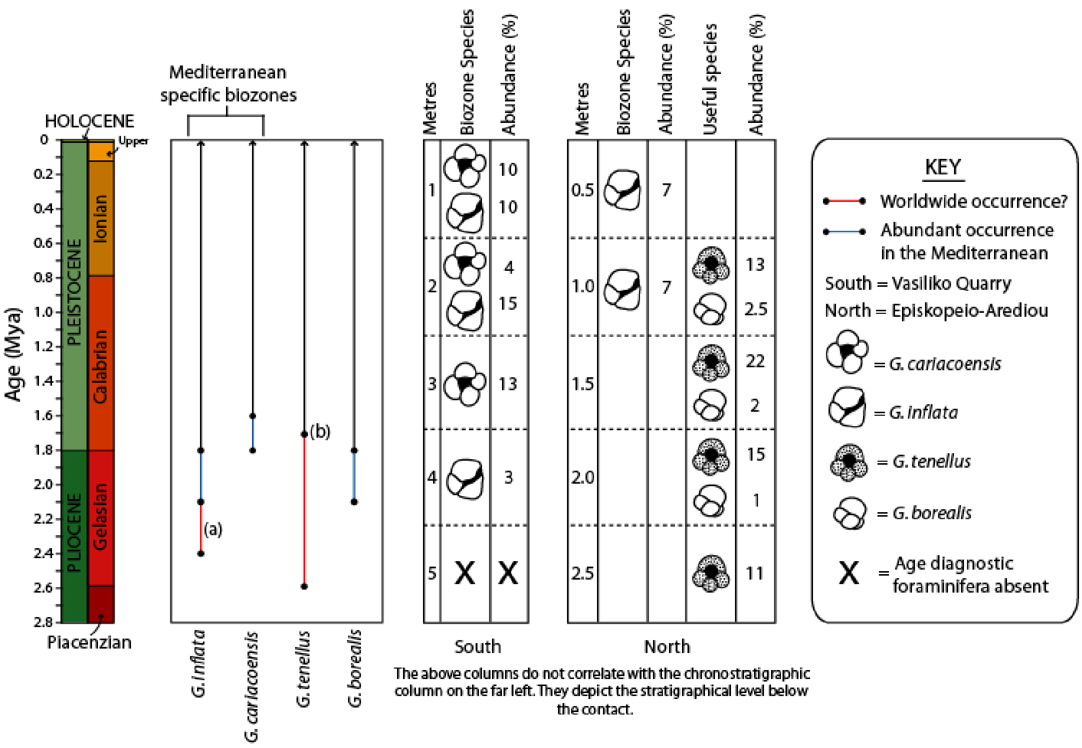


Figure 2.3 – Age diagnostic planktonic foraminiferal species present in the Nicosia Formation. Note: (a) populations of *G. inflata* did not become established in mid to high latitudes of the North Atlantic until 2.1 mya, during which this species expanded into the Mediterranean (Chapman et al., 1997) and (b) *G. tenellus* is considered to be a good marker for the early Pleistocene in the Mediterranean

This species is only present at Episkopeio-Arediou and is abundant up to 0.5 m (Fig. 2.3, Table 2.1). Reconnaissance samples from Khirokitia (Fig. 2.1) and from the top of the Nicosia Formation at Pissouri (Fig. 2.1) duplicate these results (Appendix B). It can therefore be concluded that the uppermost age of the Nicosia Formation across Cyprus conforms to a maximum late Pliocene to early Pleistocene age (1.8-2.1 mya).

2.3.2 Sedimentology

The Nicosia Formation at Khirokita and Pissouri comprises regularly bedded, fining-upward packages. Each package typically has a sharp-based fine-grained, frequently laminated sandstone/siltstone bed fining upwards into claystone (Fig. 2.4c & 2.4e). The well-defined bedding at the aforementioned localities appears to be absent at Vasiliko Quarry and Episkopeio-Arediou. Here, the deposits contain less sandstone, comprise smaller macrofossils (Fig. 2.4b), show a distinct lack of bedding and are more homogenous.

Stow et al. (1995) divided the Nicosia Formation into three units at Pissouri. A lower unit characterised by greyish-white structureless marlstones with regularly spaced intercalations of thin micritic white limestone. A middle unit showing a progressive increase in bed thickness up section and the introduction of thin siltstone/fine sandstone beds. Beds show sharp planar to erosive bases, normal grading, partial Bouma sequences and bioturbation towards the top surface. The upper unit contains medium and thick-bedded siltstones and sandstones interbedded with marlstone in relatively equal proportions. The sandstones contain similar internal structures to the middle unit, however heavily bioturbated and laminated beds are prevalent.

In addition to Stow's observations this study reports erosively based beds containing rip-up clasts, possible hummocky cross stratification and wave ripples in the middle unit (Fig. 2.4d & 2.4e). An increasingly diverse and abundant shallow marine molluscan macrofauna and microfauna (Fig. 2.4) in the upper unit appears to be coincident with an increase in fine-grained sandstone beds.

2.3.3 Interpretation

The packages are interpreted as fining upward parasequences. These exhibit a deepening upward trend and in the middle unit have been interpreted to internally display features of turbiditic origin (Stow et al., 1995; Lord et al., 2000). However, the

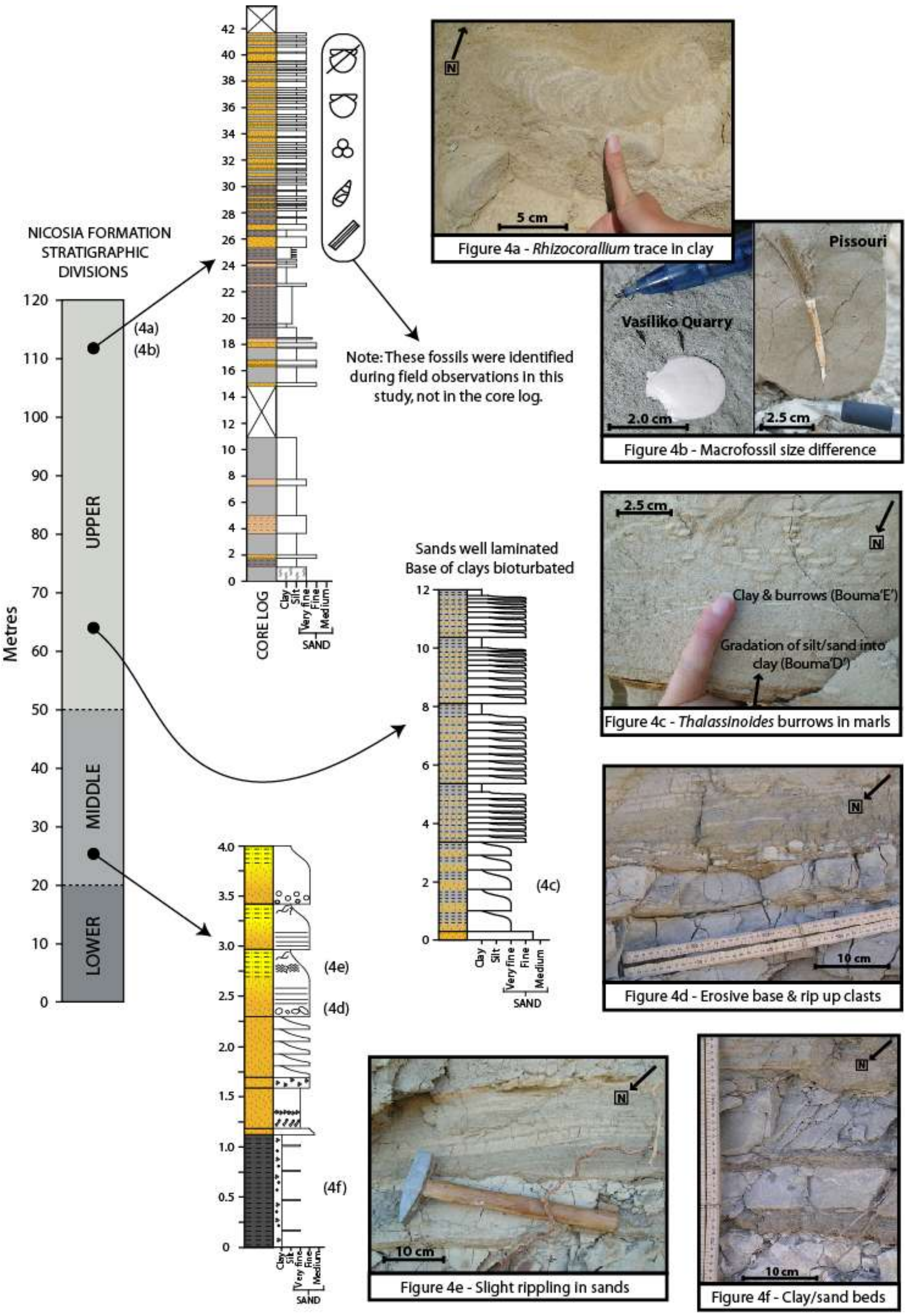


Figure 2.4 – Nicosia Formation stratigraphical context. Refer to Appendix E for a stratigraphical key for the logs

presence of erosive bases to the packages, wave ripples and abundant evidence for storm reworking indicates packages of the middle unit are tempestites and not turbidites (see Nealon, 1988 and Einsele et al., 1991 for review). This feature has been similarly identified in the bedded deposits of Khirokitia.

The trace fossils and molluscan macrofauna within the upper unit are indicative of a shallow marine setting i.e. infra-littoral to shallow circa-littoral (Stow, 2006; Miller, 2008). The increase in sand content up section, in conjunction with the appearance of a shallow marine macrofauna and the overall culmination in the overlying marginal marine fan delta deposits (Pissouri Formation) infers a shallowing. The absence of evidence for storm or tidal activity in the Vasiliko Quarry and Episkopeio-Arediou sections (key foraminifera study sites) indicates a deeper environment below storm wave base (i.e. depths greater than ~15-20 m, compared to the modern Mediterranean Sea; Cimerman & Langer, 1991). Deposition at these localities is considered shelfal, although further from the palaeoshoreline, which in the south is inferred to be just north of Khirokitia (see also Robertson, 1977).

The regularity of the lithological cyclicity appears to be recording a predictable systematic control, most plausibly related to astronomical forcing which is often expressed as lithological cycles in the sedimentary record (De Visser et al., 1989; Postma, 2001; van Vugt et al., 2001, Fischer et al., 2009 and many others). The chronostratigraphically constrained lithological cycles in Pissouri are correlated to the global eustatic sea level curve in Figure 2.5 in an attempt to understand this cyclicity. Global eustacy and the regional $\delta^{18}O$ records during this period appear to predominantly document obliquity scale changes and hence the high latitude influence of NHIS. The initiation of the regular cyclicity yields excellent agreement with the global eustatic cycles, with each cycle potentially exhibiting an ~ 41 kyr periodicity related to obliquity. This cyclicity also appears to commence at a similar time to the predicted onset of the NHIS (~ 3.0 mya), further supported by the long term shallowing in sea level and a coarsening upwards of the succession.

The age constraint at the top of the succession provides a point from which to correlate the sedimentary cyclicity with the successive changes in sea level. However, this correlation method assumes the sedimentary record is complete and therefore poses a limitation. It is acknowledged that more biostratigraphical tie points would strengthen this correlation and time series analysis could confirm the dominant mode of cyclicity.

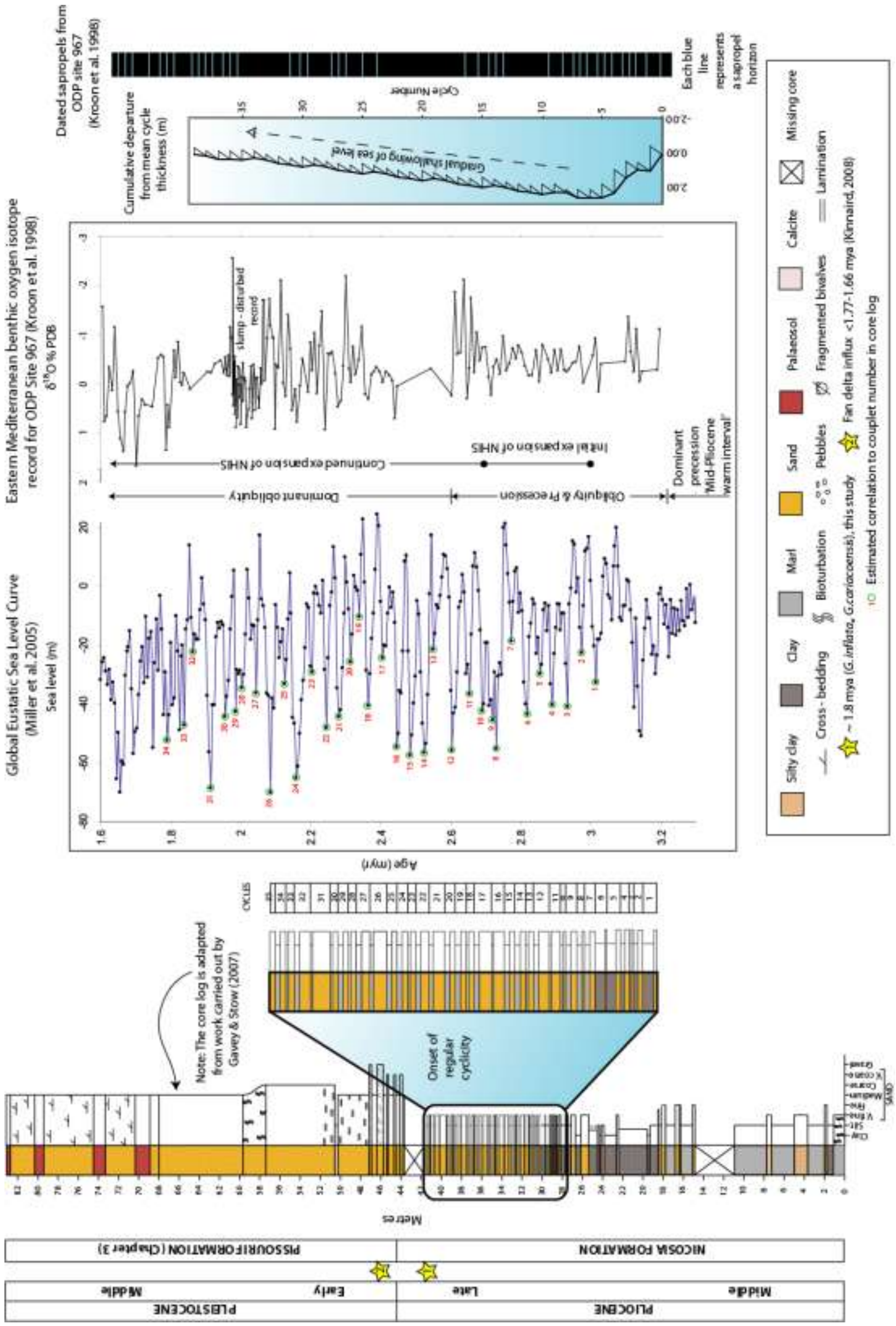


Figure 2.5 – Core log of the Pissouri road section and linkage of the cyclicity to the global eustatic sea level curve

However, a good age resolution of the cycles and an indication of sedimentation rate would be required to employ this technique and is information that was not available during this research.

2.4 Results

2.4.1 Foraminiferal palaeoecology

The ambient climate affects the hydrography of the eastern Mediterranean Sea, which in turn influences the ecosystem structure (Duarte et al., 1999). Analyses of the planktonic and benthonic foraminifera allow the recognition of key assemblages, the basic climatic interpretations of which are based upon ecologically significant index species. A list of the identified fauna and their ecological preferences are depicted in Tables 2.3 and 2.4.

Planktonic foraminifera Episkopeio-Arediou: Figure 2.6 shows the distribution of the nine palaeoecologically useful species of foraminifera identified at this locality. Two ‘Planktonic Foraminiferal Assemblage Zones’ (PFAZ) are distinguished on the basis of percentage abundances with emphasis placed on the varietal trends in the peak abundances of the included species. PFAZ-1 comprises ***G. bulloides***, *G. glutinata* and *G. siphonifera*, which display peak abundances in the lower half of the section (the bold italicised species characterize the respective assemblages). PFAZ-2 comprises ***G. ruber***, *G. rubescens*, *G. tenellus*, *G. sacculifer*, *O. universa* and *G. inflata*, which conversely exhibit maximal abundances in the mid to upper part of the section. PFAZ-1 is characteristic of a dominantly eutrophic, epipelagic-mesopelagic mixed layer in high productivity, cool shallow waters. The assemblage indicates a tolerance towards euryhaline conditions. PFAZ-2 on the other hand is dominated by *G. ruber*, a species reaching 34% of the total fauna (Table 2.1) and is indicative of a surface mixed layer under a dominantly oligotrophic regime in warm, stratified, shallow waters.

Planktonic foraminifera Vasiliko Quarry: Four major species of foraminifera were identified at this locality (Fig. 2.7). Two conspicuous PFAZ’s are identified, named as PFAZ-3 and PFAZ-4. PFAZ-3 constitutes ***G. bulloides*** and *O. Universa* with maximal abundances evident within the lowermost stratigraphical levels, with *G. bulloides* accounting for up to 58% of the assemblage (Table 2.2). PFAZ-4 comprises ***G. sacculifer*** and subordinate *G. inflata*, which peak in the up most part of the stratigraphy

(Fig. 2.7). PFAZ-3 is representative of a mixed eutrophic to oligotrophic, intermediate to surface mixed layer. It is characteristic of a euryhaline and high productivity regime, most likely associated with shallow, perhaps stratified, cool subtropical waters (Table 2.3). PFAZ-4 is a mixed oligotrophic to eutrophic, epipelagic to mesopelagic assemblage, indicative of the mixed layer and is almost certainly representative of warm subtropical waters (Table 2.3). The combination of *O. universa* and *G. inflata* may present a complication in the interpretation of the temperature signature, however is reasoned in section 2.4.2.

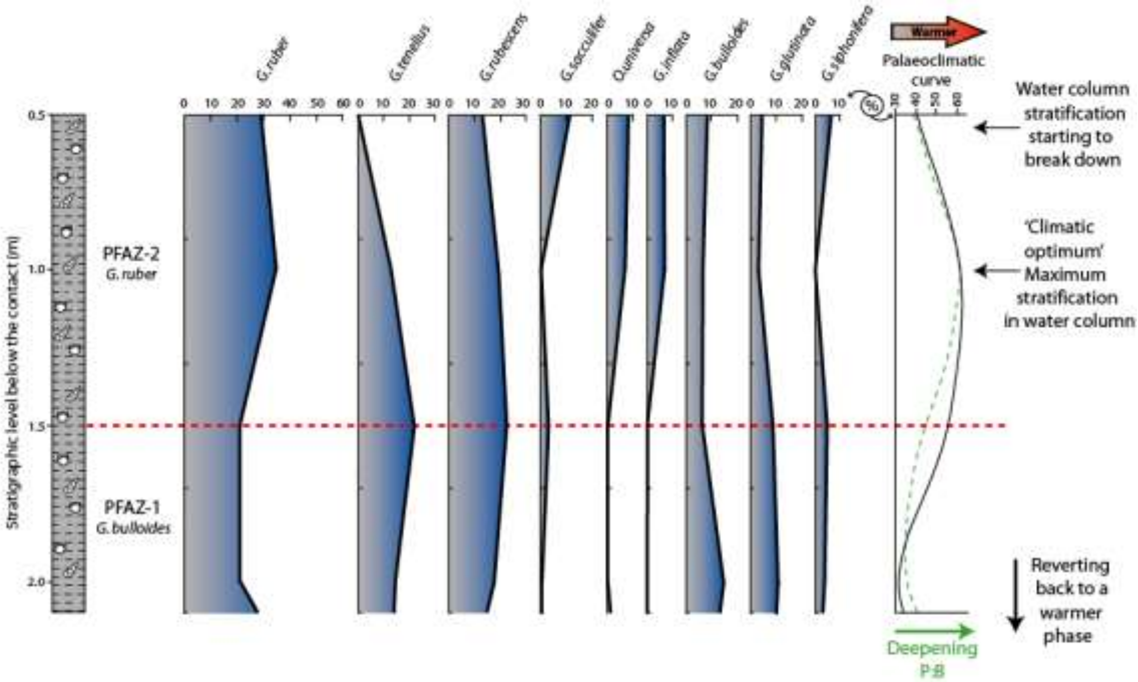


Figure 2.6 – Abundance trends of the ecologically significant planktonic species at Episkopeio- Arediou

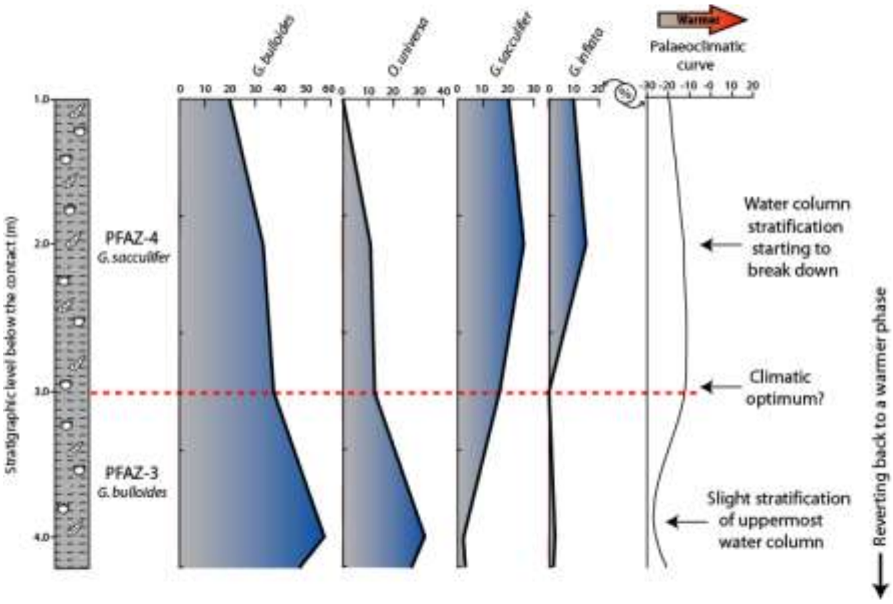


Figure 2.7 – Abundance trends of the ecologically significant planktonic species at Vasiliko Quarry

Species & key diagnostic features	Depth (m)	Ref	Trophic preference	Ref	Primary ecological preferences & characteristics	Ref
Globigerina bulloides (Plate 2.1, Figures 11, 12, 13) Trochospiral, rapidly enlarging spherical chambers, depressed sutures, perforate & spinose wall, high umbilical arched aperture, 3-5 chambers in final whorl	0-100 generally no depth preference (found above 400m)	7	E	3,6,7, 8,12	• Intermediate, subsurface mixed layer • Often related with deeper vertical mixing & to upwelling • Relient upon nutrient rich waters: a reliable high productivity indicator • Grazer • Inhabits cool subtropical waters (~16°C) • Euryhaline	3,4,6, 9,10, 18,20, 21
Globigerina rubescens (Plate 2.I, Figure 7) Trochospiral, rapidly enlarging globular chambers, radial - curved depressed sutures, perforate & spinose wall, small - high arched umbilical aperture bordered by distinct rim	>100		O	6	• Mixed layer • Predatory • Warm water	3,6,11
Globigerina siphonifera (Plate 2.I, Figure 15) Planispiral (adult), rapidly enlarging globular - ovate chambers, radial depressed sutures, perforate & spinose wall, interiomarginal aperture with broad equatorial arch, 4-6 chambers in final whorl	-	-	O & E	19 5	• Deeper water • Inhabits cool subtropical waters (~16°C), winter mixed layer • Euryhaline	3,18
Globigerinoides ruber (Plate 2.1, Figure 1 & 2) Trochospiral, rapidly enlarging subglobular chambers, depressed & radial sutures, perforate & spinose wall, interiomarginal highly arched aperture plus supplementary smaller arch shaped openings on spiral side, pink (*rosea*) & white (*alba*) varieties, 3 chambers in final whorl	0-50 usually within the top 10m of the water column	13	O	1,2,4, 6,9	• Epipelagic, dwells in the surface mixed layer • Predatory • Inhabits warm subtropical waters (~18.5 *alba* variety to 21°C *rosea* variety) • Euryhaline • Stratification of water column favours production of this species	3,6,7, 9,11, 18,20
Globigerinoides sacculifer (Plate 2.I, Figure 3 & 4) Trochospiral, spherical chambers (final chamber can have sack-like appearance), depressed & slightly curved sutures, spinose wall (honey comb pore pits), interiomarginal aperture bordered by a rim, plus supplementary apertures on spiral side, 3.5 chambers in final whorl	50-300 0-50	16 17	O	7	• Resides in surface nutrient depleted waters of surface mixed layer (generally a deeper dweller) • Present in oceanographic settings with a strong stratification of the water column • Predatory • Often associated with periods of high Northern Hemisphere insolation • Inhabits warm subtropical waters (~19.5° C) • Stenothermic	3,7,9, 11,15, 18
Globigerinoides tenellus (Plate 2.I, Figure 5 & 6) Morphologically similar to *G. rubescens*, *G. tenellus* distinguished from *G. rubescens* by a secondary small aperture on ventral side	>100 based on morphological similarity with *G. rubecens*		O	6	• Deeper waters • Predatory • Warm water	3,6,9, 11

Table 2.3 – Ecological characteristics of the key planktonic foraminifera identified. Note: E = Eutrophic, M = Mesotrophic and O = Oligotrophic

Species & key diagnostic features	Depth (m)	Ref	Trophic preference	Ref	Primary ecological preferences & characteristics	Ref
Globigerinita glutinata (Plate I, Figure 14) Trochospiral, spherical chambers, radial & depressed sutures, smooth micro-perforate wall, interiomarginal, umbilical aperture with a low arch & thin lip, umbilical bulla (final stage of test growth) 3-4 chambers in final whorl	50-100 100-200	4 14	E	5,6	• Resides in the mixed layer but can live deeper • Epipelagic to mesopelagic • Non-spinose & a grazer • Preference for cooler water masses • Euryhaline • High productivity indicator	3,6,10, 12,20, 21
Globorotalia inflata (Plate I, Figure 9 & 10) Trochospiral, inflated chambers, radial - curved depressed sutures, smooth wall with round tubercules, large interiomarginal aperture, ext-traumbilical slit with lip, 3.5-4 chambers in final whorl	0-200	4	E	5	• Generally requires strong vertical mixing & deeper waters with intermediate nutrient content • Indicative of deep winter mixing & deep water ventilation • Preference for cooler water masses, although has a wide temperature range (some indicate this species is indicative of subtropical-temperate conditions) • Mesopelagic • Grazer	3,4,9, 11,12, 23
Orbulina Universa (Plate I, Figure 8) Spherical test (double sphere if over fed), spinose & perforate wall with two pore types, 1 (2) chambers in final whorl	50-100	4,14, 17	O	7	• Predatory (young can be herbivorous) • Indicative of the summer mixed layer. In winter & spring lives in surface water (0-50m), in summer sinks to 50-100 m depth • Often associated with periods of high Northern Hemisphere insolation • Indicative of strong stratification of the water column • Wide temperature range, but generally indicative of warm conditions • Euryhaline	7,9,11

Table 2.3 continued. Numbered references, 1. Abu-Zied et al. (2008); 2. Drinia et al. (2005); 3. Rohling et al. (1993); 4. Pujol & Vergnaud Grazzini (1995); 5. Rohling et al. (2004); 6. Stefanelli et al. (2005); 7. Pérez-Folgado et al. (2003); 8. Kuhnt et al. (2007); 9. Geraga et al. (2005); 10. Drinia (2009); 11. Mercone et al. (2001); 12. Casford et al. (2002); 13. Casford et al. (2003); 14. Arnold & Parker (1999); 15. Principato et al. (2003); 16. Edelman-Furstenberg et al. (2009); 17. Capotondi et al. (2006); 18. Elderfield & Ganssen (2000); 19. Deuser et al. (1981); 20. Hemleben et al. (1989); 21. Conan et al. (2002); 22. Fenton et al. (2000); 23. Melki et al. (2010)

Benthonic foraminifera Episkopeio- Arediou: Seventeen species of foraminifera with well known ecological preferences were identified (Fig. 2.8). Two 'Benthonic Foraminiferal Assemblage Zones' (BFAZ) can be defined, exhibiting opposing trends in their peak abundance. BFAZ-1 comprises ***H. boueana***, *A.mamilla*, *T. saggitula* and *S. bulloides*, primarily displaying maximal abundances in the lower half of the stratigraphical section. BFAZ-2 shows maximal abundances in the upper half of the section and is subdivided into two subsidiary assemblages due to a multiple trend in peaks (Fig. 2.8). BFAZ-2a comprises ***V. bradyana***, *C. carinata*, *G. orbicularis* and

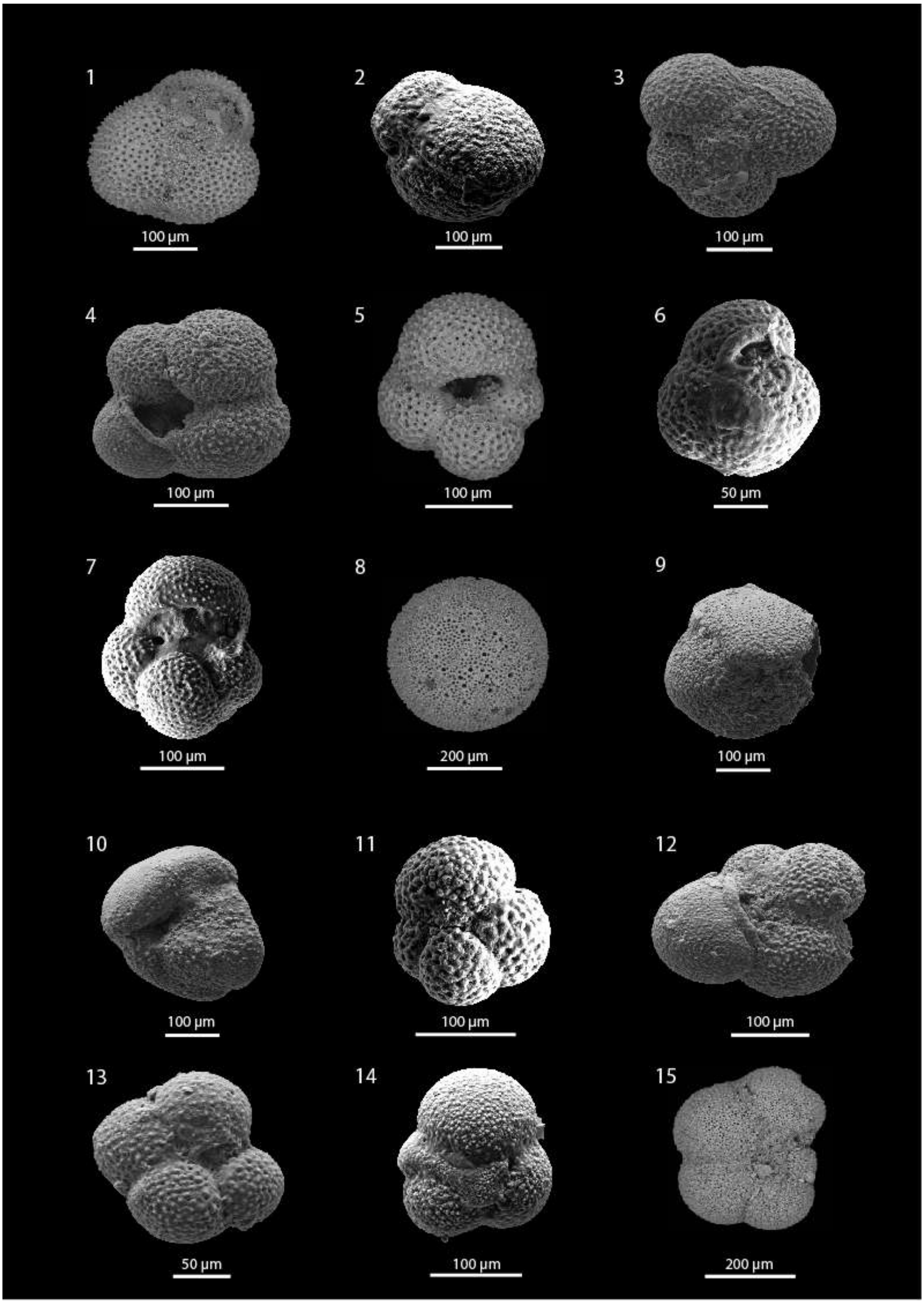


Plate 2.1 – Key planktonic foraminifera identified in the uppermost Nicosia Formation in Vasiliko Quarry and Episkopeio-Arediou

B. exilis peaking at 1.5 m, followed by BFAZ-2b comprising ***C. pachydermus***, *G. affinis*, *M. barleeanus*, *G. umbonata*, *N. labradoricum*, *A. parkinsona* and *U. mediterranea* at 1.0 m. BFAZ-1 is characteristic of a mixed oligotrophic to eutrophic, dominantly epiphytic and epifaunal assemblage in a relatively oxic environment (Table 2.4). In contrast BFAZ-2 is interpreted to be indicative of an ecologically stressed environment, with epiphytics becoming absent, in favour of species with a tolerance to high organic matter flux (Table 2.4). BFAZ-2a is collectively composed of opportunistic infaunal species and maybe reflecting the onset of ecosystem enrichment (Table 2.4). Conditions are dominantly eutrophic, of generally low oxic content with perhaps an episodic organic flux. BFAZ-2b is characterized by dominantly infaunal (some epifaunal) meso-eutrophic species, which thrive in sediments enriched in high organic matter and are abundant under low oxic conditions.

Benthonic foraminifera Vasiliko Quarry: Twelve major species of foraminifera were identified (Fig. 2.9) resulting in two evident BFAZ's (BFAZ-3 and BFAZ-4). BFAZ-3 comprises peak abundances of ***G. lamarckiana***, ***M. barleeanus***, *G. affinis*, *U. Mediterranea*, *H. balthica* and subordinate *B. striata* in the lower half of the succession. BFAZ-4 comprises ***B. aculeata***, *B. spathulata*, *N. terquemi*, *M. barleeanus* and the subordinate species *R. spinulosa*, *E. bradyi* and *Q. limbata*, exhibiting peak abundances in the uppermost part of the stratigraphy (Fig. 2.9). BFAZ-3 characterises a meso-eutrophic environment enriched in organic matter. It is dominated by infaunal species many of which show abundance under low oxic conditions. However, their concomitance with species that do not tolerate low oxic content suggests bottom waters must have a degree of ventilation. It is interpreted that conditions are perhaps relatively cool, indicated by the presence of *H. balthica*. BFAZ-4 is dominated by infaunal, meso-eutrophic species reflective of high and continuous organic matter flux (constituting 41% of the assemblage). *N.terquemi* constitutes a considerable proportion of this assemblage and is considered to only tolerate low organic matter influx (Table 2.4), however recent work in the central Mediterranean suggests this species is not significantly influenced by organic matter content (Bergamin et al., 2003).

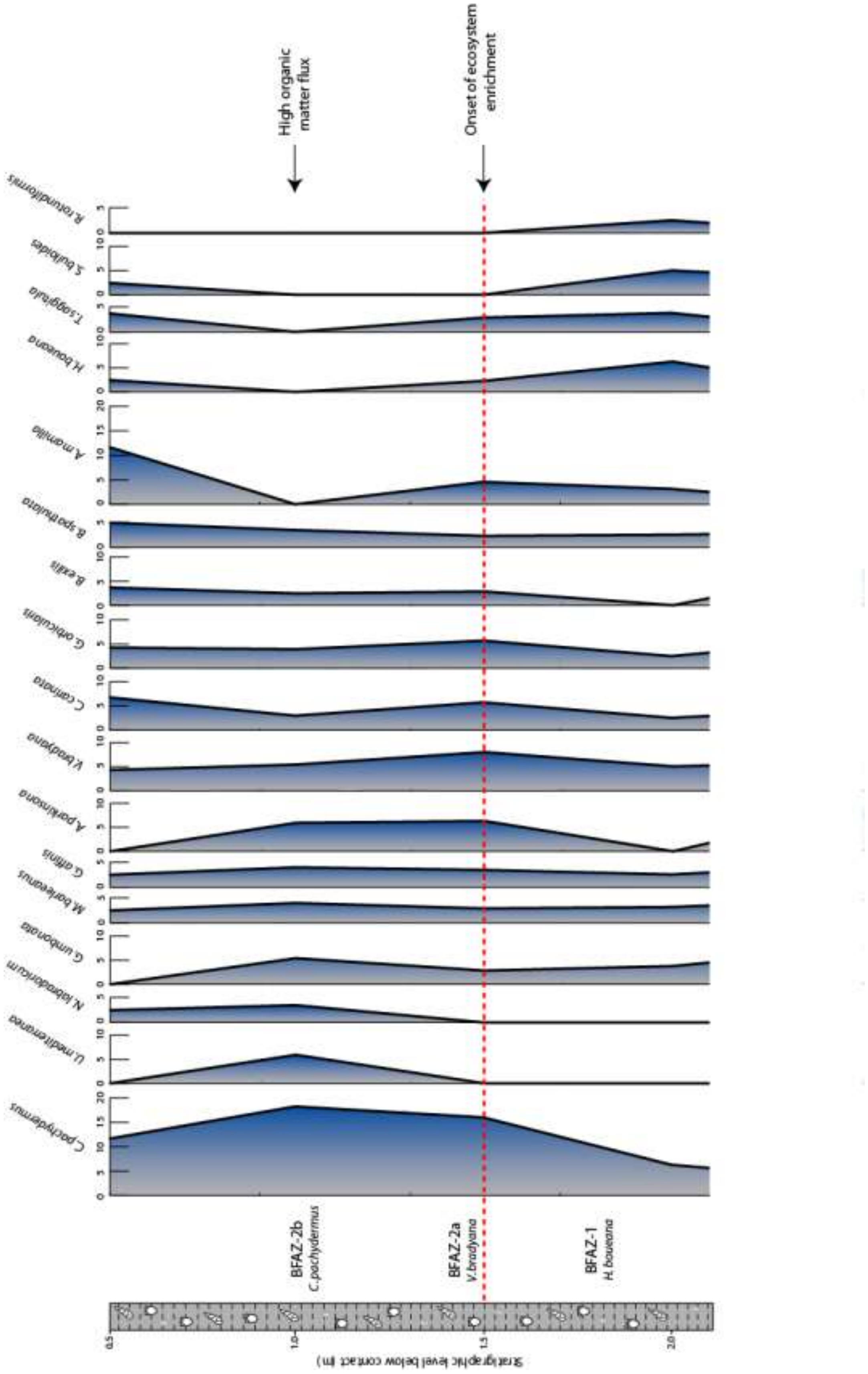


Figure 2.8 – Abundance trends of the ecologically significant benthonic species at Episkopeio-Arediou

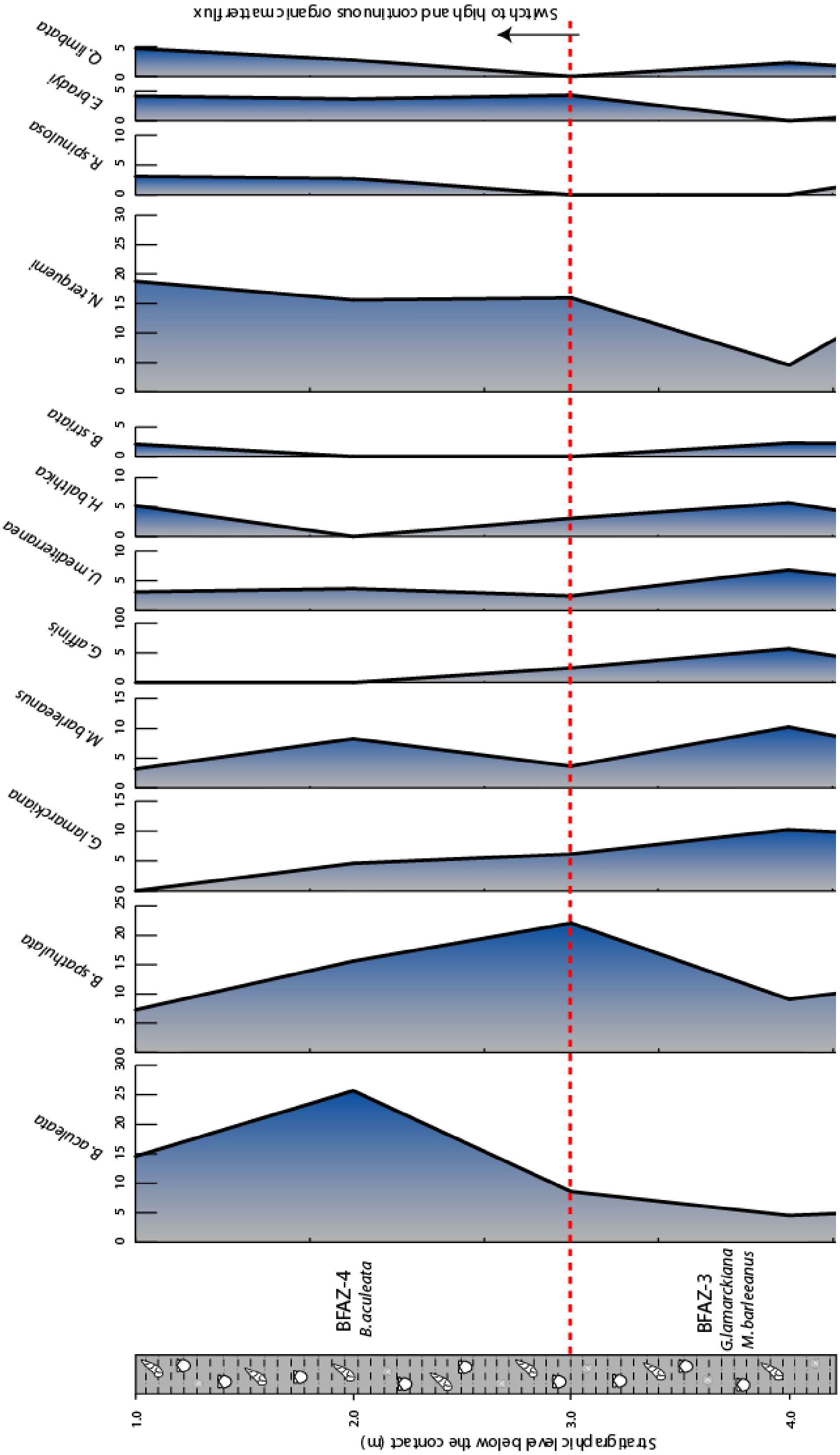


Figure 2.9 – Abundance trends of the ecologically significant benthonic species at Vasiliko Quarry

Species	Depth (m)	Ref	Trophic preference	Ref	Inf/Epi	Ref	Ox/Sub Dys	Ref	Remarks	Ref
Ammonia Parkinsona (Plate 2.2, Figure 1 & 2)	0-50		O	7	Inf	16	Dys	36,37	Tolerance to low salinity	19
Astigerinata mamilla (No image)	0-200	27	O	7	Epi	16	-	-	Epiphytic, thrives under high current activity. Can be attached to plants, sands and/or gravels	19,44, 49
Bulimina exilis (Plate 2.2, Figure 3)	-	-	E	5,6	Inf (D)	4,6,11	Dys	4,10,30,38	Known indicator of anoxia & stressed environments. Indicative of high & continuous fresh organic matter supply & stratified conditions. Often present in oxygen minimum zones	2,6,14, 15,16,33, 39,51
Bulimina aculeata (Plate 2.2, Figure 4)	5-4000	18	E	5	Inf (D)	4,5	Dys Sub	10,30,46 4,32,38	Indicative of high & continuous organic matter flux & stressed environments. Often found in oxygen minimum zones	15,16, 39
Brizalina spathulata (Plate 2.2, Figure 5)	0-45 110-211	42	M/E	14	Inf (S)	10,14	Dys Sub	10,46 38*	High organic matter flux often reflected as blooms. Indicative of stressed environments. Often found in oxygen minimum zones	16
Brizalina striata (Plate 2.2, Figure 6)	-	-	-	-	-	-	Dys Sub	46 38	Often found in oxygen minimum zones	16
Bolivina spathulata (Plate 2.2, Figure 7)	>95	22,23	E M/E	2,11,44 14	Inf (S) Epi/Inf (S)	2,4,8,9 11	Dys Sub	4,11,29 41	Preferentially lives in organic matter enriched sediments often under the influence of riverine discharge. Often present in oxygen minimum zones & indicative of stressed environments	16,26, 44, 52
Cibicides pachydermus (Plate 2.2, Figure 8 & 9)	60-4000		E	2	Epi		Ox	1	Episodic organic matter flux, generally indicative of good ventilation in bottom waters	2
Cassidulina carinata (No image)	50-3300? 60-1002	24,25,26 42	E	2	Inf (S) Epi/Inf (S)	5,14 2,15	Ox Sub/Dys	33,39 4,38*/46	Associated with strong seasonal phytoplankton bloom events, opportunistic, episodic organic flux	2,26
Eggerella bradyi (No image)	100-4000	6	M/E	6	Inf (S) Inf (S/I)	5 6	Ox Dys	23,31 36*		
Gyroidina umbonata (Plate 2.2, Figure 10 & 11)	100-150	27	M?	26?	Epi	16	Ox	33	Good ventilation of bottom waters??	
Globobulimina affinis (Plate 2.2, Figure 12)	-	-	E M/E	6 5,14	Inf (D)	1,2,4,5, 6,12,17	Dys	2,4,35	Abundant under low oxic conditions in sediments enriched in organic matter. Often indicative of stressed environments. Possibly warm, stratified conditions. Often found in oxygen minimum zones	2,14,15, 16,38,39
Gyroidina orbicularis (No image)	500-1040 100-2800 **	20,21	O O/M M	2 3,6 5	Inf (I) Epi/Inf (S)	5 6,14	Ox	1	Opportunistic, may represent first stage of ecosystem enrichment	35,53,54
Gyroidinoides lamarckiana (Plate 2.2, Figure 13 & 14)	140-4000		-	-	-	-	Ox Dys	33,48 46	Indicator of organic enrichment, doesn't tolerate low oxygen content in sediments	48
Hanzawaia boueana (Plate 2.2, Figure 15/Plate 2.3, Figure 1)	50-200	27	-	-	Epi	4	Ox Sub	33 32	Epiphytic, indicative of a vegetated sea floor	39,44
Hyalinea balthica (Plate 2.3, Figure 2)	60-4000 100-125	14 42	M/E	6	Inf (I) Inf (S/I) Inf (S)	5 6 14,44	Ox Sub Sub/Dys	41 40 33	High organic matter flux, thrives under unstable conditions, an opportunistic early colonizer, possibly indicative of water stratification, characterizes colder conditions	15,38,40, 44,47,48, 50
Melonis barleeanus (Plate 2.3, Figure 3 & 4)	-	-	E M/E	44 5	Inf (I) Inf (S/I) Inf	17 5,44 4	Sub Sub/Dys	4 44	Abundant under low oxic conditions in sediments enriched in organic matter	
Nonion labradocorim (Plate 2.3, Figure 5)	-	-	-	-	Inf	55	-	-	Strongly depends on food flux to sea floor Elevated seasonal productivity	55
Neoconorbina terquemi (Plate 2.3, Figure 6)	0-100 <15	16	-	-	Epi	16, 49	-	-	Epiphytic, thrives under high current activity with low organic matter flux. Attached to plants, sands or gravels	15,19,49
Quinqueloculina limbata (No image)	2-40	16	O/M	11	Epi Epi/Inf (S)	4,11 14	Ox	4,39	Thrives under high current activity with low organic matter flux	15,19
Rectuvigerina phlegeri (No image)	-	-	E	49	-	-	Sub/Dys	49	Oxygen limited conditions. Often indicative of stressed environments	49
Reusella spinulosa (Plate II, Figure 7)	53-60	16	-	-	-	-	Ox	39		
Rutherfordoides rotundiformis (Plate II, Figure 8)	-	-	-	-	-	-	-	-	Abundant under low oxygen conditions in sediments enriched in organic matter	2

Table 2.4 – Ecological characteristics of the key benthonic foraminifera identified. Note: E = eutrophic, M= mesotrophic, O= oligotrophic, Inf = infaunal, Inf (S) = shallow infaunal, Inf (I) = intermediate infaunal, Inf (D) = deep infaunal, Epi = epifaunal, Ox = oxic, Sub = suboxic, Dys = Dysoxic, * = based on generic level, ** highest frequencies below 600m in the Mediterranean, see Appendix C for diagnostic features

Species	Depth (m)	Ref	Trophic preference	Ref	Inf/Epi	Ref	Ox/Sub Dys	Ref	Remarks	Ref
Sphaeroidina bulloides (Plate II, Figure 9 & 10)	20-4500		E	28	Epi Inf	4 15	Ox Sub	32 4,34		
Siphonina reticulata (Plate II, Figure 11)	-	-	-	-	Epi	4	Ox	4	Possibly opportunistic	4
Textularia saggitula (Plate II, Figure 12)	60-110? 15-148		-	-	Epi	16	Dys ?	36*	Epiphytic, indicative of a vegetated sea floor	45
Uvigerina mediterranea (Plate II, Figure 13)	201-1016	16	E/M M O/M	2 5 3	Inf (S)	2,3,5,8	Ox Sub	1 4	Thrives under unstable conditions, indicative of a considerable amount of organic matter reaching sea floor & indicative of stressed environments	2,15,39
Valvulinera bradyana (Plate II, Figure 14 & 15)	40-125 50-130	19	E	5	Inf (S)	5,14,44	Sub	32	Opportunistic, prefers ecosystems enriched with high organic matter in generally low oxic environments. Indicative of stressed environments	5,15,19

Table 2.4 continued – Numbered references, 1. Casford et al. (2003); 2. Abu-Zied et al. (2008); 3. Kuhnt et al. (2007); 4. Drinia et al. (2008); 5. Fontanier et al. (2002); 6. Schmiedel et al. (2003); 7. Van der Zwaan et al. (1999); 8. Drinia et al. (2005); 9. Drinia et al. (2009); 10. Kaminski et al. (2002); 11. Morigi (2008); 12. Nolet & Corliss (1990); 13. Schmiedel et al. (2002); 14. Stefanelli et al. (2005); 15. Martins et al. (2006); 16. Murray (1991/2006); 17. Jorissen (1999); 18. Drinia et al. (2004a); 19. Frezza & Carboni (2009); 20. Cita & Zocchi (1978); 21. De Rijk et al. (1999a); 22. Mendes et al. (2004); 23. Kouwenhoven et al. (2006); 24. Hayward et al. (2007); 25. De Rijk (2000); 26. Duchemin et al. (2007); 27. Wright et al. (1975); 28. Eberwein & Mackensen (2006); 29. Kaiho et al. (2004); 30. Rasmussen (2002); 31. Schonfeld (2001); 32. Kouwenhoven & Van der Zwaan (2006); 33. Jorissen et al. (2007); 34. Kaiho (1999/1994); 35. Mercone et al. (2001); 36. Bernhard & Gupta (1999); 37. Van der Zwaan (2000); 38. McHugh et al. (2008); 39. Drinia et al. (2004b); 40. Scourse et al. (2002); 41. Pascual et al. (2008); 42. Saidova (2008); 43. Murray (2003); 44. Fontanier et al. (2008); 45. Rossi & Horton (2009); 46. Chendeş et al. (2004); 47. Combourieu - Nebout & Vergnaud Grazzini (1991); 48. Asioli et al. (2001); 49. Milker et al. (2009); 50. Evans et al. (2002); 51. Becker et al. (2005); 52. Laangezaal et al. (2006); 53. Jorissen et al. (1992); 54. Rohling et al. (1997); 55. Polyak et al. (2002)

A comparison between the sites is required; this has been achieved through consideration of planktonic foraminiferal biozones and changes in assemblage characteristics. The presence of *G. inflata* at the 4.0 m interval in Vasiliko Quarry and the appearance of *G. borealis* (a subsidiary species with the same FAD as *G. inflata*) at the 2.0 m interval in Episkopeio-Arediou provide an age constrained biostratigraphical tie point (Fig. 2.3). This suggests the sediments above 4.0 m and 2.0 m must be younger than 1.8-2.1 mya. Furthermore, the identified assemblages provide useful palaeoclimatic information and in this respect an additional correlation between the sites can be inferred. Regional effects (benthonics) were discounted by using only planktonic associations; using this method a distinctive change between cooler planktonic assemblages (i.e. the dominance of *G. bulloides*) and warmer assemblages (i.e. the prevalence of *G. ruber* and *G. sacculifer*) was revealed at the 3.0 m interval at Vasiliko Quarry and the 1.5 m interval at Episkopeio-Arediou. The presence of age diagnostic species and the ecological change has enabled two correlation points between the study localities.

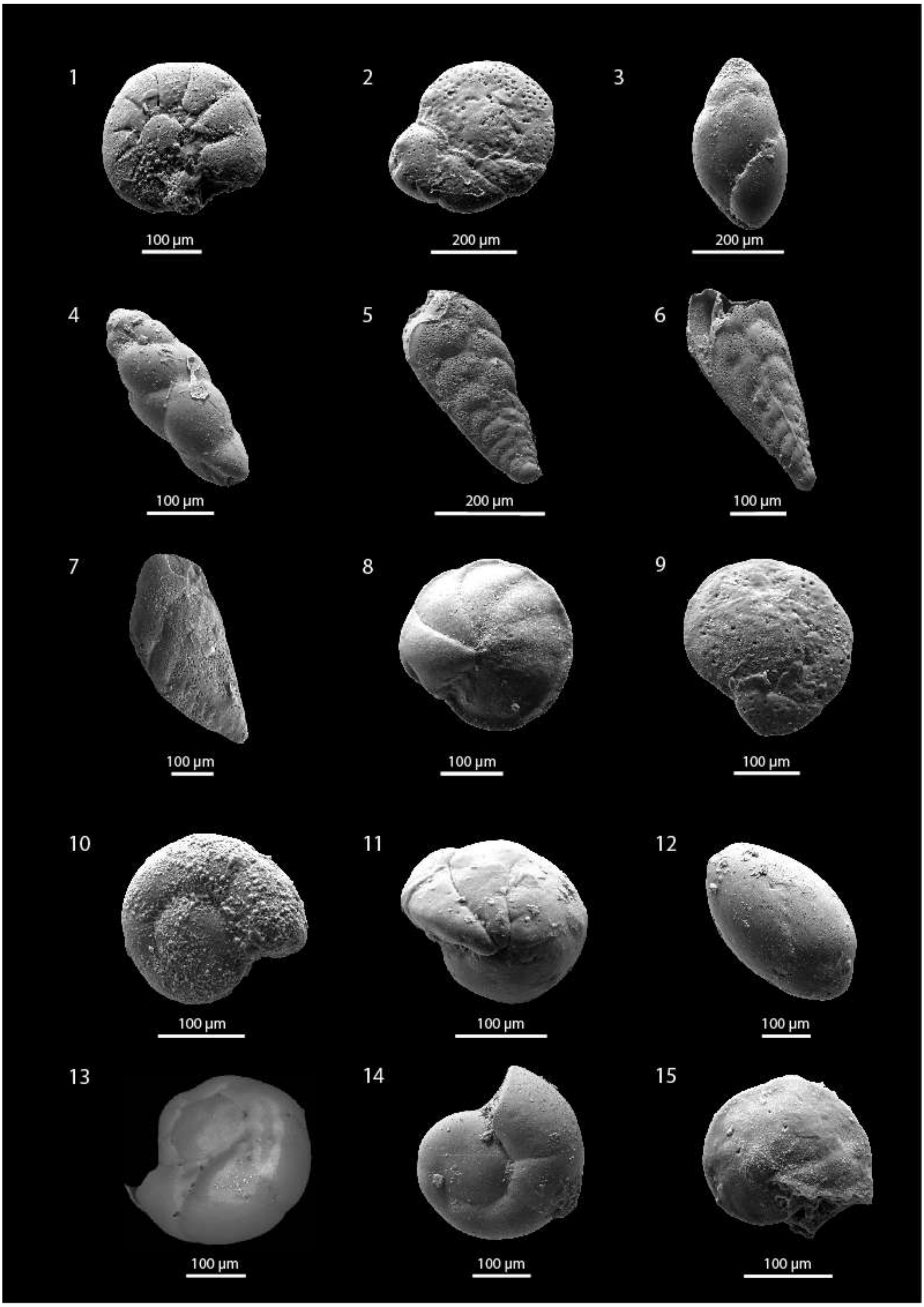


Plate 2.2 – Key benthonic foraminifera identified in the uppermost Nicosia Formation in Vasiliko Quarry and Episkopeio-Arediou

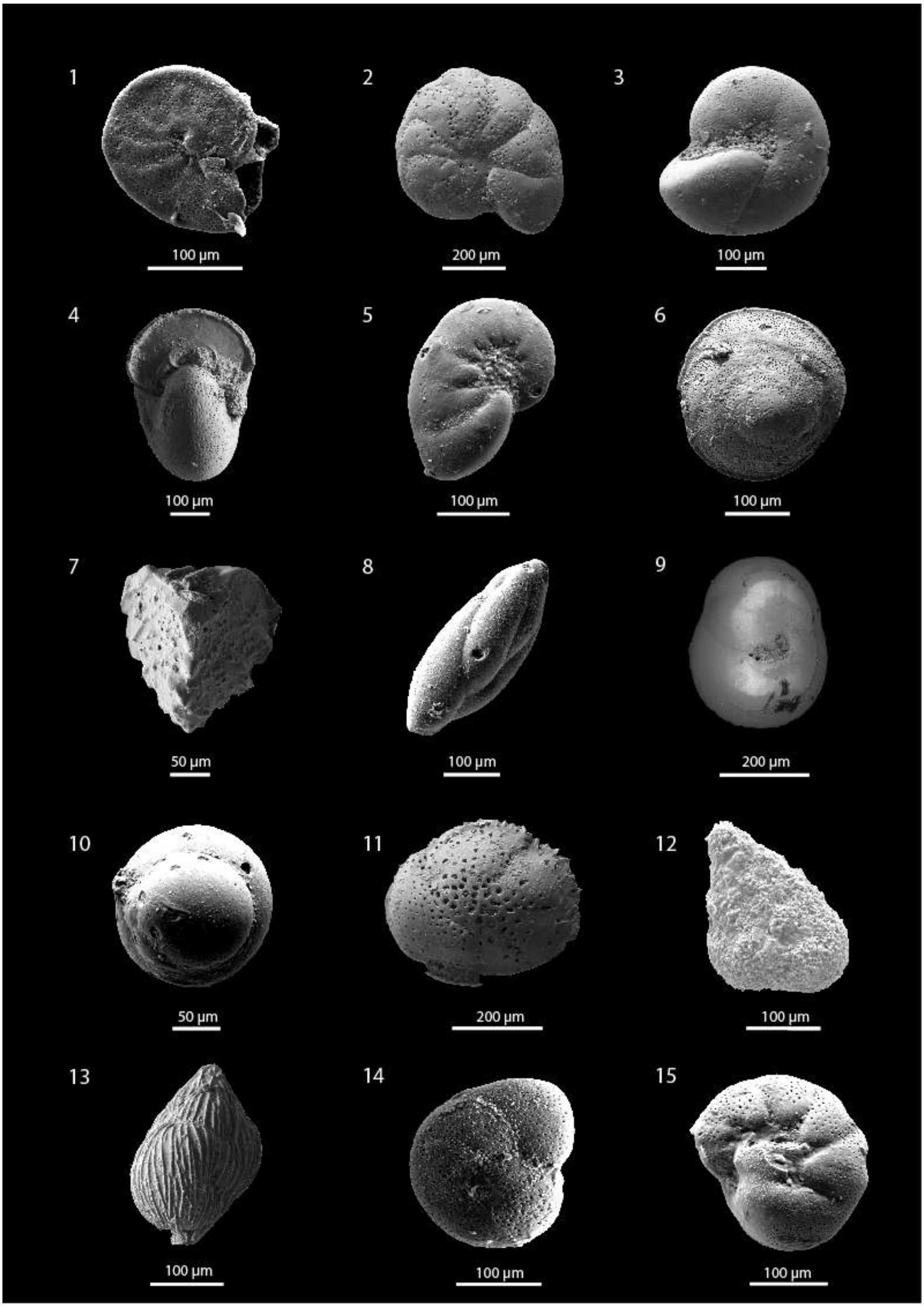


Plate 2.3 – Key benthonic foraminifera identified in the uppermost Nicosia Formation in Vasiliko Quarry and Episkopeio-Arediou

2.4.2. Climatic interpretation of foraminiferal assemblage zones

Currently the eastern Mediterranean Sea is characterised by two ecological modes, i) oligotrophic and, ii) dominantly eutrophic with a subordinate oligotrophic component. Each state has its characteristic planktonic and benthonic foraminiferal species, which specifically dominate during the respective winter and summer periods (Fig. 2.10, planktonic assemblages). For example, during the present day summer the eastern Mediterranean Sea is dominated by *G. ruber* indicating warm, oligotrophic conditions. Conversely during the present day winter, cooler water, eutrophic species such as *G. bulloides* and *G. glutinata* proliferate. Using the distribution and ecological preferences of the modern day species/assemblages, the Plio-Pleistocene assemblages identified in this study can be understood.

Ocean State 1: comprises assemblage PFAZ-1, PFAZ-3, BFAZ-1 and BFAZ-3. The abundance of *G. bulloides* at both localities and the presence of *G. siphonifera* in Episkopeio-Arediou indicates cool subtropical conditions (~16˚C; Elderfield & Ganssen, 2000), with an association of foraminifera reflective of a high productivity regime (Table 2.3). This collection of species potentially reflects, i) a coastal upwelling system, ii) strong seasonal mixing or, iii) riverine influx (Rohling et al., 1997; Pérez-Folgado et al., 2003; Geraga et al., 2005). Upwelling is a common process in the eastern Mediterranean (e.g. Aegean Sea), where intermediate waters upwell into surface waters, induced by prevailing offshore winds, primarily in the winter (Casford et al., 2002). However, riverine influx is an equally plausible source for inducing a high productivity regime, especially when considering the climate that characterises the Mediterranean today i.e. wet, cool to mild winters.

A high abundance of *O. Universa* in association with *G. bulloides* (Vasiliko Quarry) can be considered as unusual. *O. Universa* is generally indicative of warm subtropical waters, with preferential inhabitation of the nutrient depleted mixed layer under a stratified regime (Pérez-Folgado et al., 2003; Geraga et al., 2005). However, this species is eurythermal and euryhaline (Table 2.3) and may therefore not be sufficiently diagnostic of specific watermasses. Nonetheless, the very low percentages and or absence of *G. sacculifer* support the cool analogy, since to the south of Cyprus this species disappears when the surface water temperature drops below 17-18°C (Luz & Reiss, 1983; Edelman-Furstenberg et al., 2009). Furthermore, peak abundances in

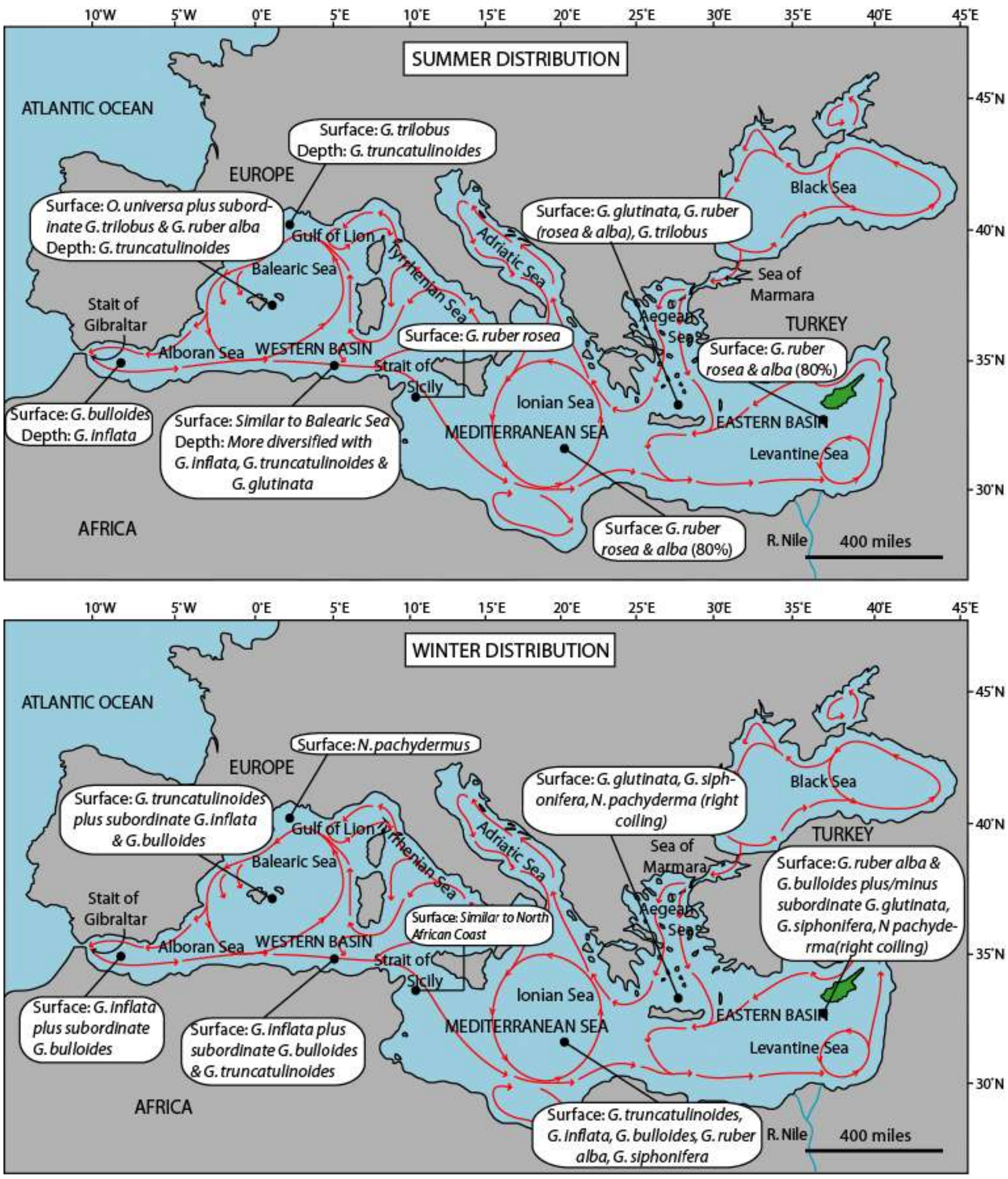


Figure 2.10 – Summer and winter distribution of dominant planktonic foraminifera in the modern Mediterranean Sea. Data from Pujol & Vergnaud Grazzini (1995), red arrows denote circulation patterns.

G. bulloides have been recorded during analogous cold conditions in the Mediterranean e.g. Younger Dryas (Asioli et al., 2001).

It is likely the high productivity conditions are related to riverine influx rather than to an upwelling analogy, with particular reference to the south. This is based upon the abundance of *O. universa* and hence stratification of the uppermost surface waters (Table 2.3). Stratification would suppress the effects of nutrient upwelling (e.g. Sobarzo et al., 2007), it is therefore conceived that high productivity is the direct consequence of freshwater influx.

The benthic foraminifera at the Episkopeio locality exhibit a relatively high abundance of epifaunal and epiphytic species such as *H. boueana*, *C. pachydermus*, *A. mamilla* and *T. saggitula,* in conjunction with the non-epiphytic species *S. bulloides* (Table 2.4). This grouping is characteristic of well-oxygenated, vegetated areas with high current activities and is reflective of relatively favourable bottom water conditions (lowest percentage of stress indicators; Fig. 2.11). On the other hand many of the species at Vasiliko Quarry are indicative of unfavourable conditions, with an abundance of foraminifera symptomatic of high organic matter flux and relatively suboxic conditions e.g. BFAZ-3 (*G. lamarckiana*, *M. barleeanus*; Table 2.4). In this locality the dominance of infaunal benthics and stress indicators, accompanied by lower diversity and higher dominance, compared to Episkopeio-Arediou, suggests an ecologically stressed habitat (Fig. 2.11 & 2.12, Nolet & Corliss, 1990; Jorissen et al., 1995; Kouwenhoven, 2000; Schmiedel et al., 2003; Drinia et al., 2005; Abu-Zied et al., 2008).

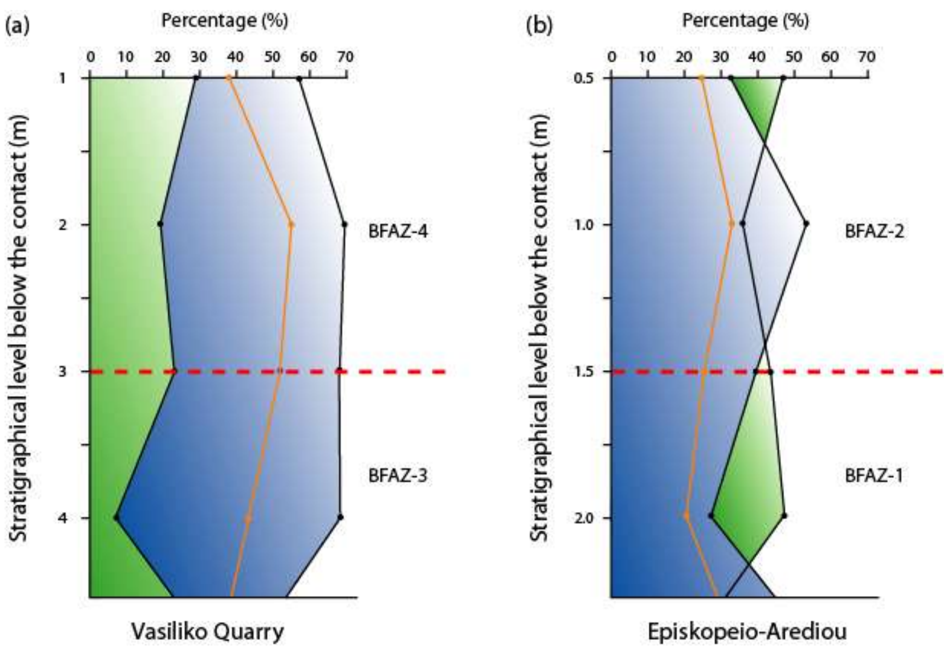


Figure 2.11 – Percentages of epifaunal and infaunal foraminifera in the study localities, including degree of environmental stress. Green shading = epifauna, blue shading = infauna, orange line = stress.

In all probability the stressed conditions are likely to be related to the influx of organic matter through freshwater input (e.g. analogous to periods of sapropel formation), thus supporting the conditions reflected in the planktonic assemblages.

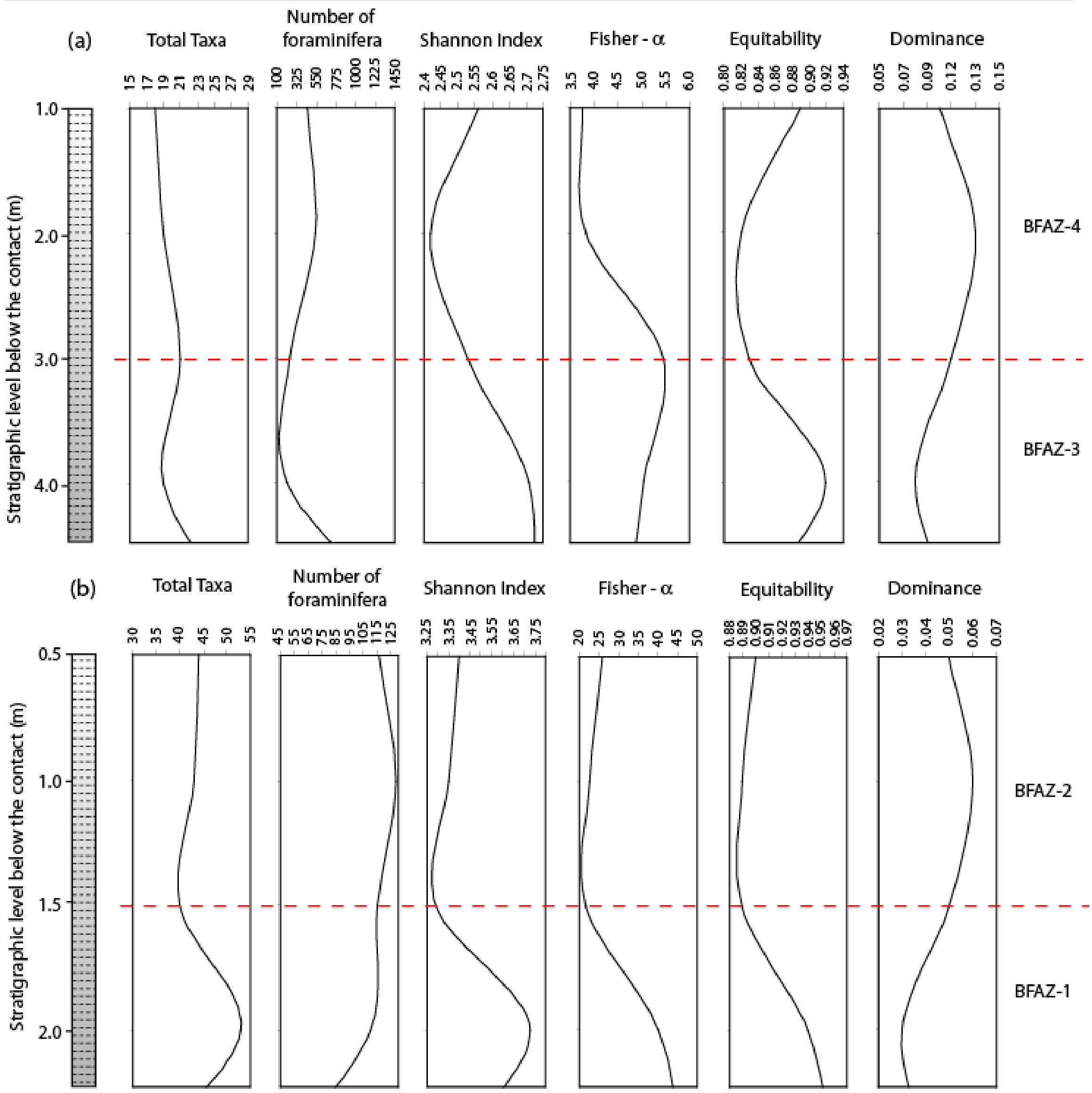


Figure 2.12 – Diversity trends for benthonic foraminifera in a) Vasiliko Quarry and b) Episkopeio-Arediou

In conclusion, Ocean State 1 is indicative of relatively cool subtropical conditions in a high productivity, generally eutrophic, relatively shallow water shelfal regime, perhaps under the influence of high riverine runoff (particularly to the south), comparable to the present day winter runoff pattern (Appendix D). Planktonic foraminifera such as *G. bulloides*, *G. glutinata* and *G. siphonifera* thrive under such conditions, particularly during the winter (Conan et al., 2002; Rohling et al., 2004), as indicated by the modern equivalents in the eastern Mediterranean (Fig. 2.10; Pujol & Vergnaud Grazzini, 1995). The inferred sea surface temperature (SST) for Ocean State 1 conforms with the present day winter average SST of 16-17˚C (eastern basin, Tziperman & Malanotte-Rizzoli, 1991) and with cool/glacial SST's for the last 650 ka, which equate to ~15˚C (Emeis et al., 1998).

Ocean State 2: comprises assemblage PFAZ-2, PFAZ-4, BFAZ-2 and BFAZ-4. The profound increase in *G. ruber* at Episkopeio (Fig. 2.6) in conjunction with other warm water indicators, the significant enrichment of *G. sacculifer* and a drastic decrease in *G. bulloides* abundance at Vasiliko (Fig. 2.7) indicates the establishment of much warmer conditions (~19.5-21˚C; Elderfield & Ganssen, 2000) and water column stratification (Table 2.3). Stratification of the water column is frequently induced by warm atmospheric conditions, a process that can be equally promoted by freshwater runoff during periods of enhanced precipitation (Geraga et al., 2005; Sangiorgi et al., 2006; Nijenhuis & de Lange, 2000). The significant freshwater influx and subsequent formation of a low salinity lense may induce a shoaling of the pycnocline (Rohling & Hilgen, 1991; Van Os et al., 1994; Becker et al., 2005) and appears to be reflected in the planktonic assemblages. For example, *G. sacculifer* is frequently associated with the presence of a shallow pycnocline (Reiss et al., 1999; Fenton, 2000; Principato et al., 2003; Geraga et al., 2005; Triantaphyllou et al., 2009), whilst *G. ruber* is a species often indicative of reduced salinity lenses (Capotondi & Vigliotti, 1999; Rohling et al., 2002a; Lourens et al., 2004), observed in areas such as the Orinoco river, Venezuela (Stefanelli et al., 2005).

The benthic community in Episkopeio-Arediou exhibit a significant change in ecological characteristics in comparison to Ocean State 1. This change is associated with an increase in the abundance of infaunal species and stress indicators, accompanied by a decrease in diversity and increase in dominance (Fig. 2.11b & 2.12b), thus reflecting deterioration in environmental conditions. The Vasiliko Quarry assemblages are similarly indicative of unfavourable conditions recording a significant decrease in diversity, coeval with a considerable rise in dominance (Fig. 2.12a). Infaunal abundance only slightly increases (already high in Ocean State 1), whilst species indicative of stress prevail (Fig. 2.11a). Based upon the presence of specific species within these assemblages, the most likely cause of environmental deterioration was due to a more continuous delivery of organic matter and the subsequent reduction in oxygenation.

A three-stage process appears to be evident in the progression of both the planktonic and benthonic assemblages, most clearly demonstrated in Episkopeio-

Arediou. An initial increase in abundance of warm planktonic species (e.g. *G. tenellus*, *G. rubescens* and *G. sacculifer*) and a benthic abundance of opportunistic fauna indicative of ecosystem enrichment (Table 2.3 & 2.4, Fig. 2.8) is interpreted to be a response to the initial onset of warm, wet conditions. This is followed by a 'climatic optimum' and maximum stratification of the water column, exemplified by the profound increase in *G. ruber* (*rosea* variety?) (e.g. Principato et al., 2006), concurrent with high organic matter flux and full enrichment of the ecosystem (benthics). This culminates in a signature likely to represent the beginning of the break down of water column stratification. A process characterized by increasing diversity, decreasing dominance (Fig. 2.12) and increasing abundance of *G. sacculifer* and *G. inflata,* thus indicating a shallow pycnocline immediately followed by a well mixed water column (Principato et al., 2006). This trend is accompanied by the reappearance of more oxyphilic and/or epiphytic benthic species, perhaps in response to the initiation and return towards a cooler climate.

In conclusion, Ocean State 2 is related to warm subtropical conditions with high runoff, testified by the abundance of the endemic warm water species *G. ruber*, the oligo-eutrophic stressed conditions, lowered diversities and inferred high organic matter influx. The SST deduced for Ocean State 2 corresponds well with the ~21˚C average SST deduced for warm/interglacial periods over the past 650 ka (Emeis et al. 1998). The deepening trend reflected in the planktonic:benthonic ratio from Ocean State 1 to 2 provides additional evidence for an interglacial analogy (Stefanelli et al., 2005; Fig. 2.6), when sea level is expected to rise. The assemblages identified are similar to those recorded in the Mediterranean during the warm and wet early Holocene (e.g. Asioli et al., 2001), whilst a comparison to the present day summer assemblages (eastern Mediterranean) indicates a similarity with respect to the proliferation of planktonic, oligotrophic, spinose (predatory) species (particularly *G. ruber*; Pujol & Vergnaud Grazzini, 1995; Stefanelli et al., 2005). However, the eutrophic component reflected in the benthics indicates a 'wet' summer signature, which is on the contrary to present-day conditions in the eastern Mediterranean (Giorgi & Lionello, 2008; Rohling et al., 2009). The warm and wet signature demonstrates analogous conditions considered apt for sapropel formation (precession index minima, Northern Hemisphere insolation maxima), although the resolution of this study is not suitable for identifying these deposits. The intensification of the precipitation regime during these periods promoted a significant freshwater influx into the Levantine Basin, thus weakening the anti-estuarine circulation and reducing oxic content (Emeis et al., 1998; Kroon et al., 1998; Rohling et al., 2000).

2.5 An integrated climate-ocean model for the Plio-Pleistocene of the eastern Mediterranean: Discussion

This study proposes that sedimentary cyclicity and foraminiferal palaeoecology can be used to reconstruct the ocean-climate state in the Levantine Basin. The Plio-Pleistocene (1.7 to 2.1 ma) interval can be divided into two timeslices and oceanographic states. During the earlier interval (Ocean State 1) the north of Cyprus was characterized by dominantly eutrophic, cool subtropical conditions under the influence of minor runoff. To the south similar conditions prevailed, although runoff is considered to be more significant (greater water column stratification, higher productivity). In the later interval the north and south were both characterized by oligo-eutrophic, warm subtropical temperatures and conditions indicative of high runoff (Ocean State 2).

Currently Cyprus has a characteristic Mediterranean climate i.e. wet, cool winters and hot, dry summers, with seasonal precipitation differing regionally between northern (Mesaoria plain) and southern areas of the Troodos Mountains. In the winter most rainfall runs off the steeper southern slopes of the Troodos Massif directly towards the Levantine Basin (Appendix D), influenced by the southeasterly track of the winter cyclones. Conversely, during the summer very warm conditions prevail, particularly in the Mesaoria Basin, where air gets trapped between the Kyrenia Mountain range and the Troodos, inducing humid conditions and consequently rainfall. The south on the other hand remains almost bone dry with limited moisture sourced from isolated thunderstorms (Appendix D). This climatic pattern is attributable to the oscillations in the atmospheric cells, the boundaries of which lie directly over Cyprus. During the summer Cyprus is under the influence of the descending portion of the subtropical, dry Hadley Cell whilst during the winter, cool and moisture bearing mid-latitude westerlies of the Ferrel Cell dominate. Based upon this, it is interpreted that the present day winter Mediterranean climate (insolation minima, hot dry summers and mild to cool wet winters, Duarte et al., 1999; Rohling et al., 2009) provides an analogue for Ocean State 1. This is in agreement with estimated (glacial) late Pliocene rainfall in the central Mediterranean, which was considered to be on a comparable scale to the present day

(Klotz et al., 2006). However, Ocean State 2 does not correlate with the presently dry, summer conditions of the south. Deviations from the modern day summer regime are evident within the Levantine Basin, where organic rich sediments termed 'sapropels' are found. These occur in discrete and regularly spaced bundles and are directly related to periods of enhanced freshwater flux (Rohling & Hilgen, 1991; Bar-Matthews et al., 2000; Kallel et al., 2000) during periods of strong summer insolation (compared to the present day, Rohling, 1994). Minima in the precession index and eccentricity maxima (Rohling & Hilgen, 1991; Kroon et al., 1998; Bar-Matthews et al., 2003; Larrasoaña et al., 2003) induce strong Northern Hemisphere summer insolation, enhancing the contrast between the seasons in the Northern Hemisphere (e.g. Rohling et al., 2009). This consequently leads to stronger winds in the Mediterranean area (Principato et al., 2006) and development of Atlantic born Mediterranean depressions, which track eastwards towards Cyprus and enhance rainfall during summer seasons (Lamb, 1966; Rohling, 1994; Scrivner et al., 2004). Precipitation was greater than evaporation during these periods, creating an additional buoyancy gain, high organic matter influx into the Levantine Basin and reduction in the ventilation of bottom waters (Rohling et al., 2000; Stratford et al., 2000; Casford et al., 2003). Ocean State 2 is thus comparable to climatic conditions akin to periods of high Northern Hemisphere insolation, and is confirmed through correlation with the insolation curve, eustatic sea level and the oxygen isotopic record (Fig. 2.13).

Figure 2.13 indicates interglacial-glacial cyclicity during this period was on an obliquity scale (between 41-56 kyr), forming distinctive warm and cool phases, composed of three or four obliquity cycles (~160-210 kyr). In this study it is therefore hypothesized that the transition between warm and cool conditions corresponds to the longer-term oscillations in the Hadley and Ferrel Cells (discussed further in Chapter 5). These cells are temperature sensitive, their dynamics would therefore be fundamentally connected to North Atlantic climatic variability and sensitive to the waxing and waning of the NHIS throughout the Pliocene and Pleistocene (e.g. Gupta et al., 2003; Armstrong et al., 2009). It would be expected that during warmer periods in the Northern Hemisphere i.e. boreal summer (austral winter) the Hadley cell would dominate, conversely during boreal winter (austral summer) the Ferrel cell and mid-latitude westerlies are more likely to prevail, with alternations occurring on seasonal, orbital and geological timescales. It can therefore be extrapolated from the observations

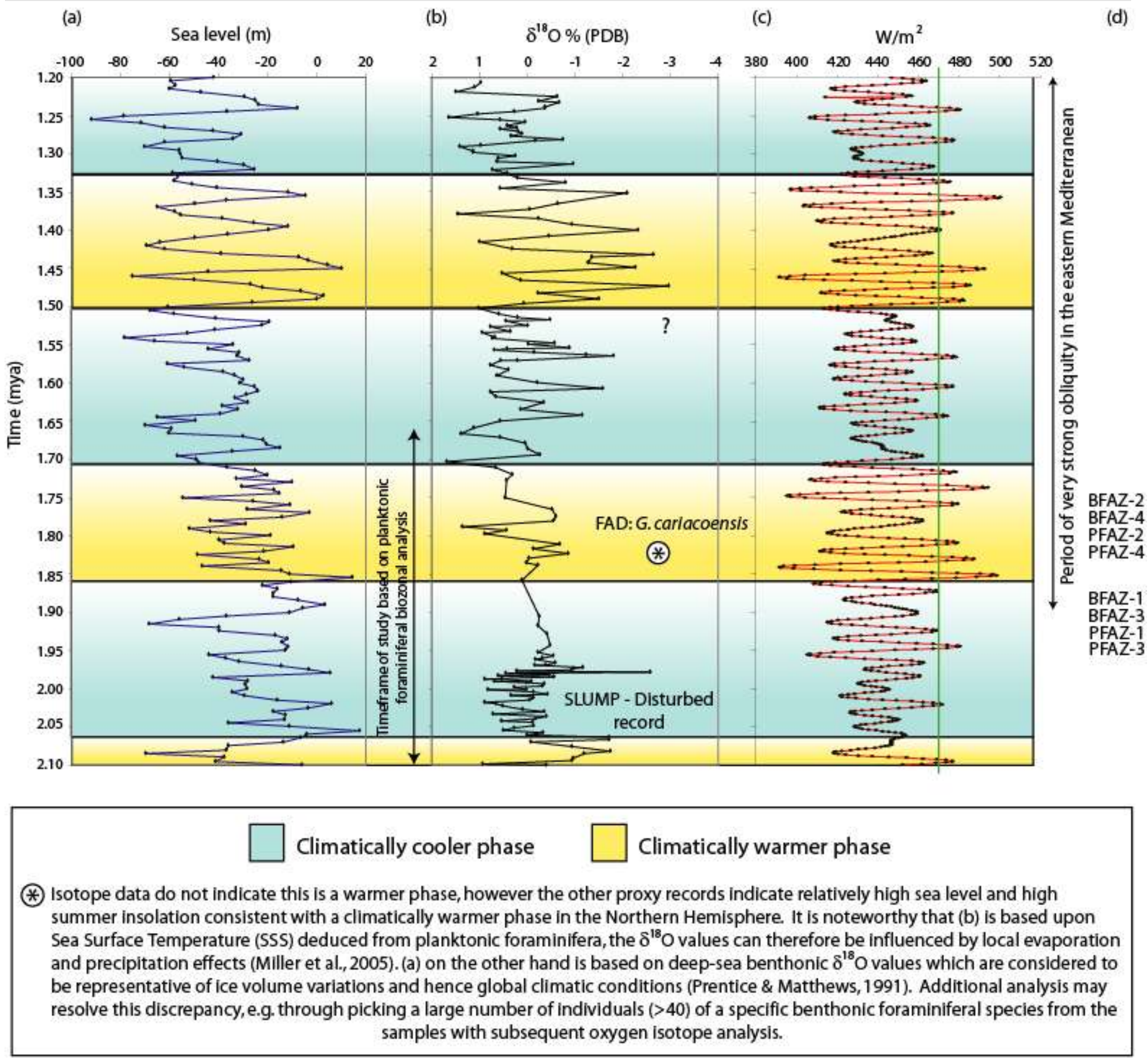


Figure 2.13 – Correlation of foraminiferal assemblage zones to the global eustatic sea level curve, oxygen isotopic record and Northern Hemisphere insolation variations. Note: (a) global eustatic sea level curve from Miller et al. (2005), (b) eastern Mediterranean oxygen isotope curve from ODP 160, Site 967 in Kroon et al. (1998), (c) Northern Hemisphere summer insolation at 65˚N (July), calculated from Laskar et al. (2004). The vertical green line represents the threshold value for Atlantic born summer Mediterranean cyclogenesis. For each graph values trending to the left indicate cooling, (d) Foraminiferal assemblage zones (this study)

that the upper part of the Nicosia Formation records climatically induced microfaunal changes, documented in the form of two end member ocean states. These changes are recorded as a shift from cooler conditions (Ocean State 1), likely to be corresponding to the expansion of the NHIS (cooler and lower sea level) and therefore periods of boreal winter dominance (Fig. 2.14a), shifting to an opposing warmer period (Ocean State 2). During the warmer interval, perhaps analogous to periods of general ice ablation, boreal summer conditions dominated, and Mediterranean depressions prevailed (Fig. 2.14b). It is therefore concluded that during the Plio-Pleistocene the ocean states and hence changing climatic conditions recorded in Cyprus reflect orbitally induced changes in the location of the Hadley and Ferrel Cells, the implications of which are discussed in detail in Chapter 5.

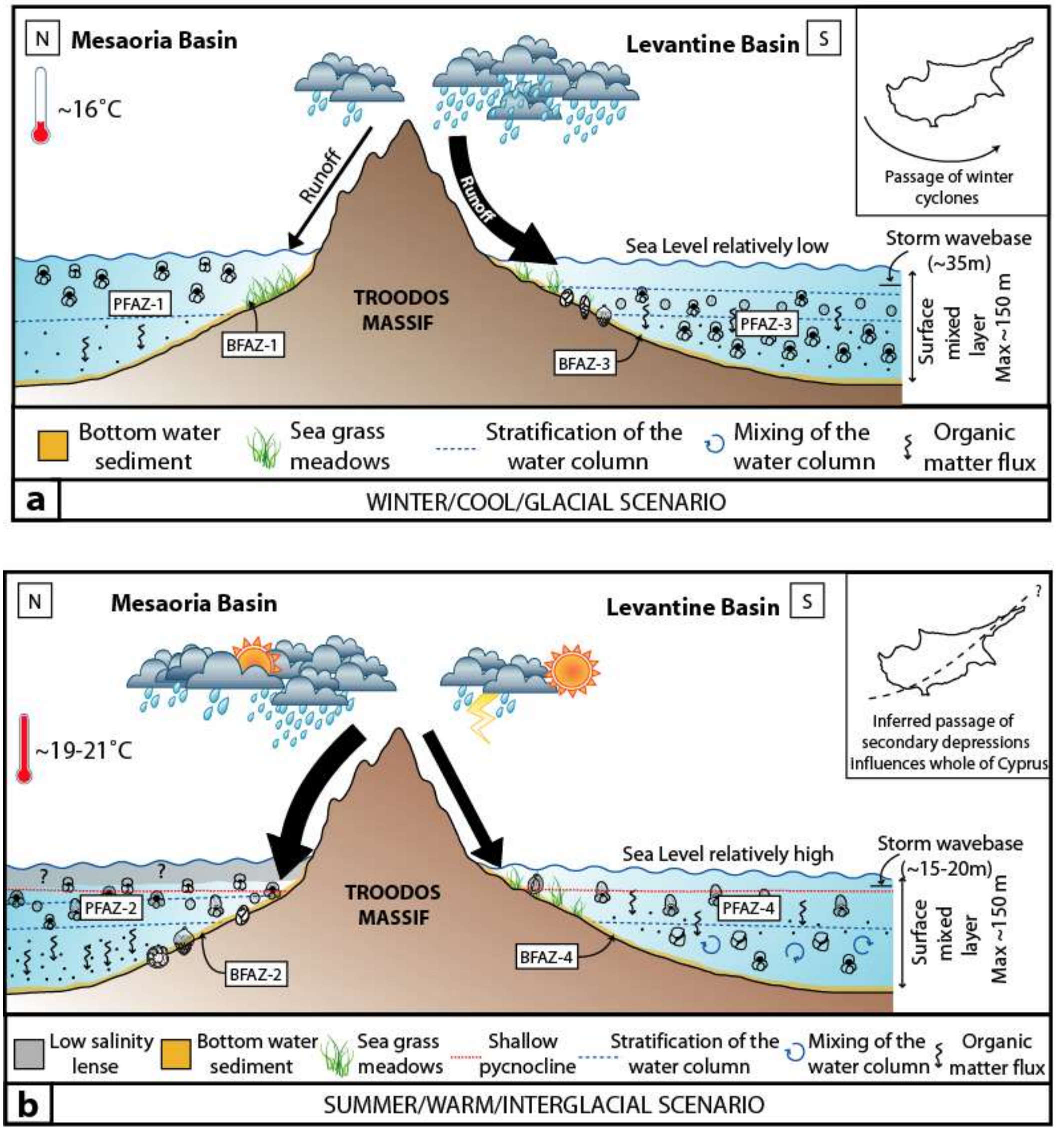


Figure 2.14 – Climatic conditions and associated foraminiferal assemblages in northern and southern Cyprus during the Plio-Pleistocene

2.6 Conclusions

Identification of age diagnostic foraminifera in the upper part of the Nicosia Formation provides an unequivocal maximum late Pliocene to early Pleistocene depositional timeframe (~ 1.8-2.1 mya). This indicates the Nicosia Formation was deposited during a critical period in Earth's history, concomitant with the expansion of the NHIS.

Analysis of the relative abundances and variability in trends between both planktonic and benthonic species has allowed the recognition of two specific coupled atmosphere-ocean end member states, discernible in both northern and southern Cyprus. A cyclic shift from cool to warm conditions indicates a systematic climatic control in the late Pliocene to early Pleistocene of the eastern Mediterranean.

In this study it is proposed that oscillatory, latitudinal movements in the Hadley and Ferrel atmospheric cells, were related to variations in the NHIS, resulting in atmosphere-ocean re-organizations in the eastern Mediterranean. The unique position of Cyprus lying at the boundary between the descending portion of the subtropical, dry Hadley Cell and the cool, moisture bearing mid-latitude westerlies of the Ferrel Cell has allowed the recognition of this cyclical pattern. In this study it is therefore concluded that changing foraminiferal ecology is consistent with shifts in the climate belts. Ocean State 1 conforms to cool subtropical conditions and dominance of the Ferrel Cell, mirroring the present day winter conditions and reflecting expansion of the ice sheets. Conversely, the warm subtropical conditions of Ocean State 2 are analogous with general ice ablation and Northern Hemisphere insolation maxima, when the Hadley Cell dominated and Mediterranean summer depressions prevailed.

During this timeframe obliquity exerted a considerable control, associated with the growth of the NHIS and is reflected in the lithological cyclicity of the mid to uppermost Nicosia Formation. In the proxy records of the eastern Mediterranean, obliquity bundles (composed of 3/4 obliquity cycles) with a ~160-210 kyr periodicity reveal cyclical perturbations in temperature, reflected in foraminiferal assemblages. It is inferred that these cycles are related to the longer-term variations in the sensitivity of the atmospheric cells to the growth of the ice sheets. It is therefore suggested that in the late Pliocene to early Pleistocene the eastern Mediterranean Sea recorded climatic scale variations, revealed as specific oceanic conditions, thus potentially indicating the relative positioning and dominance of the latitudinal location of the respective atmospheric cells.

Chapter 3

Sedimentary evolution of a braided fan delta complex (Pissouri Basin, Southern Cyprus) during Pleistocene sea level change

Abstract

The Pissouri Basin in southern Cyprus exhibits a shallowing upwards succession in the hanging wall of the Cyprus supra-subduction zone, where a sequence of shallow marine silts and fluvio-deltaic sandstones culminate in raised beach and alluvial fan deposits. This study focuses on the cyclically bedded fluvio-deltaic succession, the depositional architecture of which is hypothesized, by previous studies, to be related to a dominant tectonic control (a hypothesis that is widely applied to the sedimentary infill of the Quaternary basins in Cyprus). However, deposition of the fluvio-deltaic sandstones (~1.8 to ~0.42 mya) was coeval with a phase of major climatic change, thus leading to a new hypothesis that the cyclicity within the deposits may be attributable to a climatic control.

Sequence stratigraphical analysis of the fluvio-deltaic deposits has been undertaken; determination of parasequences indicates intercalated palaeosol horizons denote the location of sequence boundaries and abandonment of the fan delta, thus allowing a reconstruction of the relative sea level curve. Overall, a reduction in accommodation is evident in the form of successively thinner beds suggesting gradual infilling of the basin during a period of sea level fall and tectonic quiescence.

Sequence stratigraphical analysis of the Pissouri fluvio-deltaic deposits has revealed the repetitive and preferential preservation of the lowstand systems tract (LST), in an overall regressive regime. The systematic correlation of the parasequences to oscillations in the global eustatic sea level curve suggests orbital forcing, on a short eccentricity periodicity as the primary control on the internal stratigraphical cyclicity of the fluvio-deltaic succession. Parasequences (2-6) correlate with glacial maxima when wetter, cooler conditions prevailed in the eastern Mediterranean, indicating sediment flux of the parasequences was climatically controlled, on a periodicity in response to the effects of the Middle Pleistocene Transition and continuing expansion of the Northern

Hemisphere Ice Sheets. The results conform to depositional patterns recorded in analogous Mediterranean wide middle to late Pleistocene sedimentary successions.

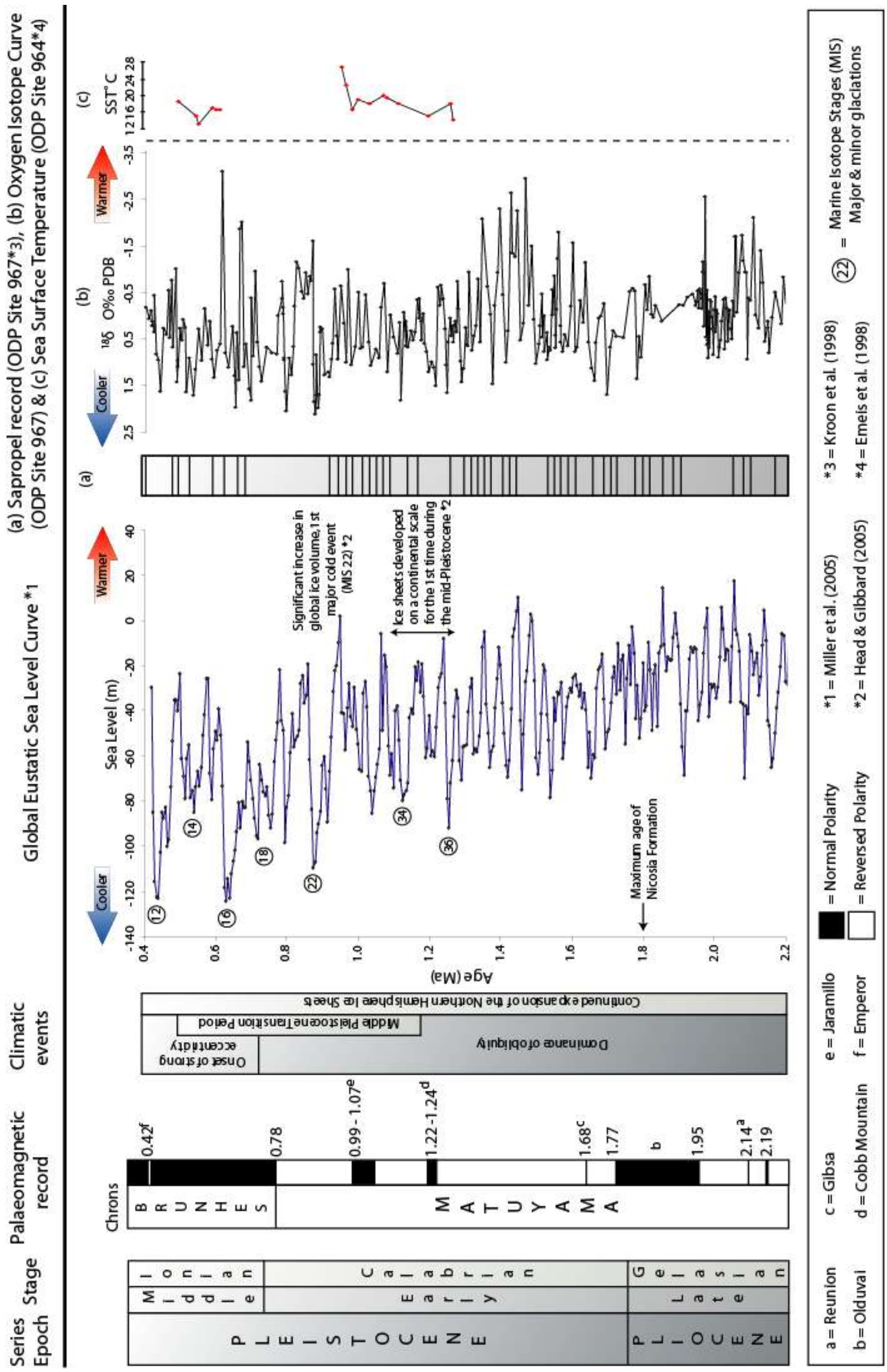
3.1 Introduction

Fan deltas are a common feature in areas undergoing active extension where hinterland uplift provides accumulated sediment supply and accommodation (Leeder et al., 1988; Ito, 1989; Fernández & Guerra-Merchán, 1996). Tectonic uplift is commonly considered to be the dominant causal factor in the development of fan deltas, influencing the style of sedimentation and their internal facies architecture (Massari & Colella, 1988; Frostick & Reid, 1989; Jones et al., 1999). Climate, however, can have an equally important controlling influence on the rate of sediment supply and the generation of accommodation through changes in precipitation intensity, vegetative stability (e.g. Frostick & Reid, 1989; Jones, 2002; Pope & Wilkinson, 2005) and eustatic sea level (Leeder et al., 1988; Postma, 2001; Van Dijk et al., 2009). The ability to distinguish tectonic from climatic influence on sedimentation can however be difficult (McCallum & Robertson, 1995; Chough & Hwang, 1997; Shanley & McCabe, 1998; Jones et al., 1999; Gupta & Cowie, 2000; Frostick & Jones 2002; Bridge, 2003; Kelling et al., 2005), unless either tectonic or climatic histories are known in detail. A key consideration for differentiating between the tectonic and climatic influences on fan successions is the different timescales over which these processes operate (Peper & de Boer, 1995; Coe, 2005). For example, climatically induced eustacy and resulting sedimentary cyclicity typically occurs in a regular manner expressed by Milankovitch (orbital) timescales of 100/400 kyr (eccentricity), 41 kyr (obliquity) and/or 19/23 kyr (precession) (3rd to 5th order respectively). In contrast tectonic ‘geophysical’ events tend to occur over longer periodicities (2nd order and above) and are expressed in a more infrequent and irregular fashion.

The Plio-Pleistocene climatic evolution is well known for the eastern Mediterranean and provides an opportunity to elucidate the primary controls on fan delta deposition in this area. During this period major climatic change occurred with the onset of the Northern Hemisphere Ice Sheets (NHIS) ca. 2.7-3.0 mya (Maslin et al., 1998; Willis et al., 1999; Marlow et al., 2000; Miller et al., 2005; Lisiecki & Raymo, 2007) and the Middle Pleistocene Transition (MPT) ca. 1.2 mya (e.g. Clark et al., 1999; Head & Gibbard, 2005). Both had a strong influence on the eastern Mediterranean, exerting considerable effects on global sea level, circulation patterns and nutrient levels as recorded in the eastern Mediterranean sapropel and $\delta^{18}O$ benthic foraminifera records (Fig. 3.1). Progressive lowering of eustatic sea level occurred with expansion of the NHIS and a strong Milankovitch cyclicity is identifiable in the oscillations of the climate and ocean record. Throughout the early Pleistocene climatic perturbations were primarily controlled by ice sheet variations on the orbital periodicity of obliquity (Head & Gibbard, 2005; Raymo et al., 2006). Post the MPT climate became strongly modulated by eccentricity (Lisiecki & Raymo, 2007) and the well-known i-cycles, as recorded by sapropel clusters (Kroon et al., 1998). From this point onwards a cyclic 'saw tooth' geometry is evident in the global eustatic sea level curve (Fig. 3.1). Long-lived glacial build-ups became characteristic of this time with comparatively transient interglacials. Consequently a notable defining feature of Mediterranean Pleistocene successions is the volumetric dominance of falling stage and lowstand deposits, with highstands representing <10% of the last 800 kyr (Massari et al., 1999; Chiocci, 2000; Hernández-Molina et al., 2000; Trincardi & Correggiari, 2000).

In this study the record of fan sedimentation is compared to the well-documented climatic record of the eastern Mediterranean, an approach similarly adopted by Skene et al. (1998) and Piper & Aksu (1992). The key test is in the ability to correlate the global eustatic sea level curve to the deposits. Using facies analysis I detail the depositional architecture of the Pissouri fan delta (PFD), reconstruct relative sea level to test the climatic control on this succession, and show that parasequences correlate with global patterns of eustatic change. The frequency and periodicity of the sedimentary cyclicity in the PFD is critical evidence for the correlation of sedimentary events to the climate record. Proxy records indicate the eastern Mediterranean is climatically sensitive to global variations in ice sheet volume and solar insolation (Kroon et al., 1998 and references within). It would therefore be predicted that climatically controlled sedimentary cycles in the PFD would correlate with sea level changes on the 3rd to 5th orders. Analogous setting studies indicate it could also be dominated by falling stage or lowstand deposits separated by sequence boundaries at either an obliquity or eccentricity scale (e.g. Massari et al., 1999). It is concluded that glacio-eustatic climate changes at the Milankovitch-scale are the predominant cause of depositional architecture in the fan delta.

Figure 3.1 – Global eustatic sea level and oxygen isotopic changes plus climatic phenomena during the timeframe of fan delta deposition in the Pissouri Basin



3.2 Geological Context

The PFD is located in the hanging wall of the Cyprus supra-subduction zone, adjacent to the uplifting Troodos Massif. During the late Miocene basin differentiation in southern Cyprus occurred during a period of active extension resulting in the formation of linked half grabens (Fig. 3.2b; Orszag-Sperber & Rouchy, 2000; Robertson, 2000), the Pissouri basin is one such structure. It is a small fault-bounded depression elongated NW-SE and widens in a southerly direction towards the Levantine Basin (Fig. 3.2c, Rouchy et al., 2001).

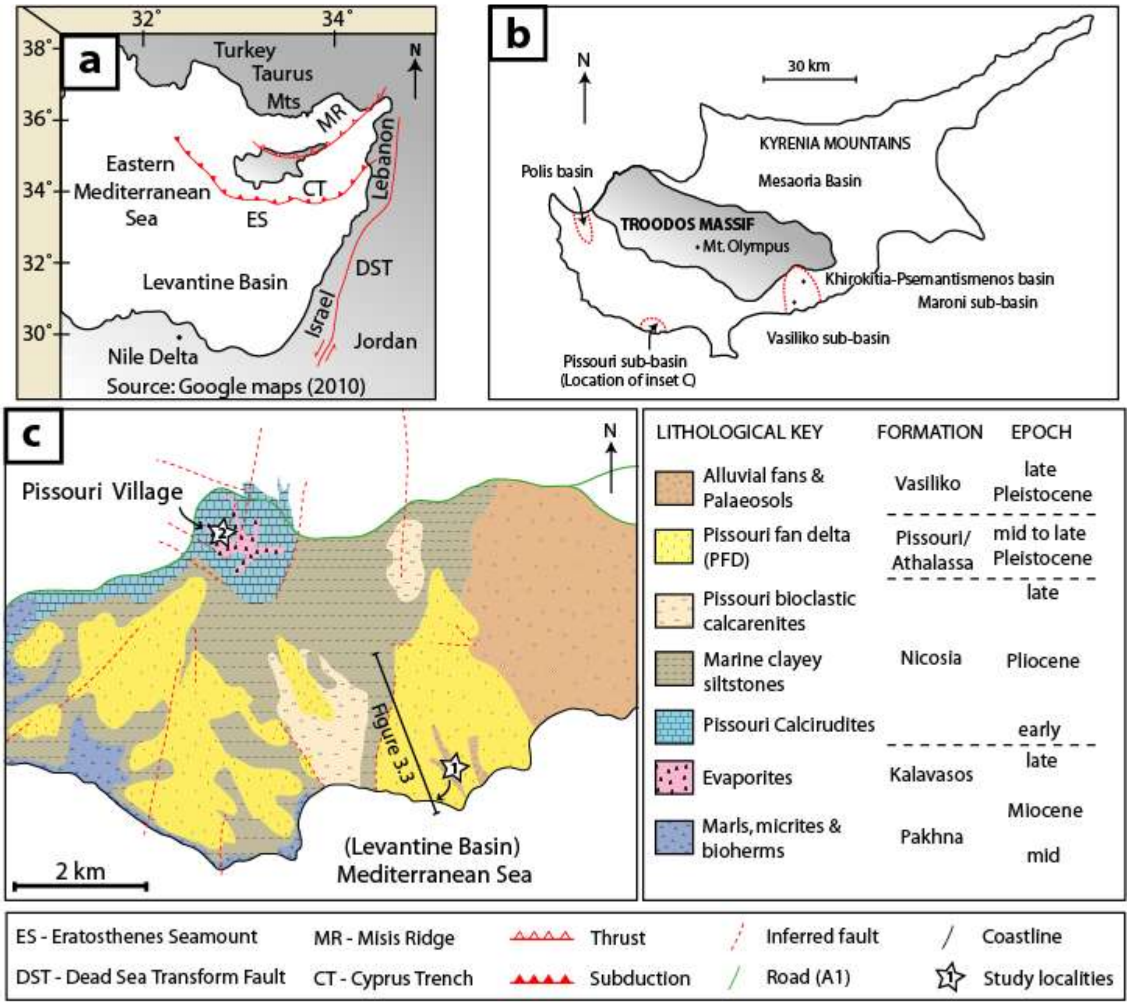


Figure 3.2 – Tectonic setting and geological context of the Pissouri Basin, southern Cyprus. Inset C is based on Stow et al. (1995)

The fan delta succession under investigation is ~ 50 metres thick and is overlain by non-marine calcrete and alluvial deposits of the Vasiliko Formation (Fig. 3.2c). The marginal marine to fluvio-deltaic deposits of the PFD are attributed to the Pissouri/Athalassa Formation (Stow et al., 1995) and are founded on early Pliocene to early Pleistocene shelfal marine clayey silts of the Nicosia Formation (Chapter 2). The Pliocene-Recent sedimentary infill therefore records a general pattern of regression, a sequence that is widespread across the island (e.g. Poole & Robertson, 1991). The marked facies change between the Nicosia and Pissouri Formation, in conjunction with faulting within the top of the clayey silts documents evidence of regional uplift at the Plio-Pleistocene boundary. A bioclastic calcarenite unit exhibiting a partially contemporaneous and partially incisional relationship with the uppermost Nicosia Formation (Stow et al., 1995) and channel cutting at Khirokitia and Amathus (Houghton et al., 1990; Robertson, 1998), further substantiates basin margin faulting and uplift during this timeframe.

3.3 Methodology

A detailed sedimentological study of the Pleistocene sediments of the Pissouri Basin has been carried out in two areas (Fig. 3.2c), localities based on the excellent exposures. Detailed graphic logs (Appendix E) were measured at a centimetre scale, noting grain size, colour, roundness and angularity of grains, degree of sorting, sedimentary structures and fossil content. Vertical and lateral facies relationships were also taken into account.

A photomosaic of the Pissouri beach section was constructed to facilitate detailed architectural analysis of the deposits. Primary bounding surfaces were determined, providing an indication of the relative timescales of deposition that were involved and helping to differentiate between allocyclic and autocyclic processes (Miall, 1996). Thin sections for each individual bed allowed a quantitative determination of the temporal variation in bioclastic content, degree of carbonate cementation and helped establish the provenance of the bioclastic material.

Based on these observations, facies were characterized and grouped into facies associations to define depositional environments. Sequence boundaries and individual parasequence packages were then identified to elucidate relative sea level change. Assignment of sea level orders was applied to gain an appreciation of the relative timescales involved and their relation to tectonic or climatic processes. The application of specific sea level orders and their periodicities are not intricately defined (see Vail et al., 1991; Duval et al., 1992; Coe, 2005), however, interpretation of sea level in this study follows Coe (2005), i.e. 3rd order sequences are depicted by 0.2-5 Ma periodicities with 4th order in the region of 0.1-0.2 Ma.

An additional investigation involved the qualitative assessment of sediment supply rate (using sedimentary structures), as it is considered to exert the major control on the stacking pattern in a basin's stratigraphical record (Allen & Hovius, 1998; Leeder et al., 1998; Weltje & de Boer, 1998; Goodbred et al., 2003).

3.4 Chronostratigraphy

The maximum age of the PFD is early Pleistocene, based on the presence of the planktonic foraminifera *G. cariacoensis* (~1.8 mya, Iaccarino, 1989) in the underlying Nicosia Formation (Fig. 3.3; Chapter 2). This conforms to palaeomagnetic dating of the first Gilbert type delta or calcarenite body (Fig. 3.3) by Kinnaird (2008), who tentatively suggests influx less than 1.77 mya. A preliminary minimum age of ~52 kya has been determined through U/Th analysis of the first calcrete horizon overlying the fan delta sediments (Table 3.1). Raised beaches deposited during incision of the fan delta help further refine the minimum age.

Sample description	Location	$\delta^{234}U$	±	^{238}U	±	^{232}Th	±	^{230}Th	±	$(^{230}Th/^{232}Th)$	Uncorrected Age	Corrected Age	±	Age error	Lab #
	(cm/top)	(‰)	(‰)	(µg/g)	(µg/g)	(ng/g)	(ng/g)	(pg/g)	(pg/g)	(activity ratio)	(ka)	(ka)	(ka)	(%)	
Calcrete horizon overlying Pissouri Fan Delta	~2.0	94.6	6.6	0.17	0.004	28.91	0.11	28.91	0.010	8.10	56.3	51.9	4.5	8.7	4701

Table 3.1 – U/Th analysis of the calcrete horizon overlying the PFD. Age uncertainties are given at the 2σ level. Decay constants are from Cheng et al. (2000)

Four raised beaches (coincident with alluvial fan deposition) have been mapped throughout southern Cyprus at heights of <3, 8-11, 50-60 and 100-110 metres above sea level (m.a.s.l.). The two lowermost beaches at <3 and 8-11 m.a.s.l. have been dated by Poole & Robertson (1991) at 116-134 kya and 185-204 kya respectively and correspondingly correlate with interglacials MIS 5 and 7. The older raised beaches are assumed to correlate with the preceding interglacials at ~310 kya (MIS 9) and ~410 kya (MIS 11) in response to the 100 kyr eccentricity control (Appendix F). All of these terraces have been identified constraining the PFD (Fig. 3.3), the deposition of the fan delta therefore occurred from early Pleistocene (~ 1.8 mya) to its abandonment in the middle Pleistocene (~ 0.42 mya).

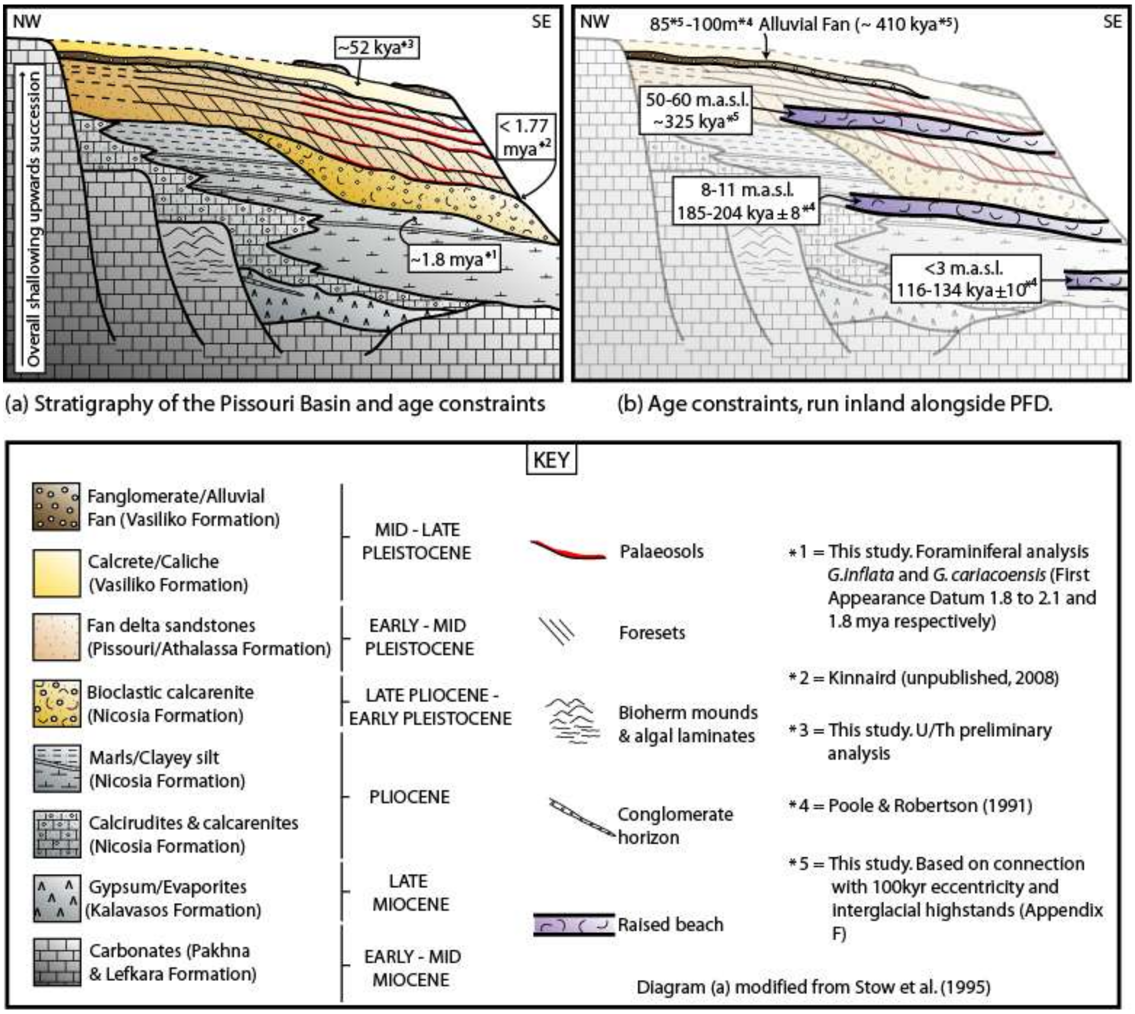


Figure 3.3 – Schematic representation of the stratigraphy in the Pissouri Basin and age constraining boundaries of the Pissouri Fan Delta

3.5 Allocyclic and autocyclic controls on deltaic deposition

Stacked and repetitive cyclic deltaic geometries such as the architecture displayed in the PFD can be the product of several mechanisms, which can be categorized into either allocyclic or autocyclic control (Dorsey et al., 1997; Johnson & Graham, 2004; Catuneanu et al., 2008; Longhitano, 2008). Extrabasinal allocyclic processes, represented as climatically or tectonically controlled fluctuations in sediment supply (and associated eustatic base level variations) are frequently considered responsible for rhythmic deposition (Cecil, 2003; Van Dijk et al., 2009), with tectonics and eustacy most commonly cited (e.g. Burns et al., 1997; Chough & Hwang, 1997; Cecil, 2003; Breda et al., 2007). Intrabasinal autocyclic controls however, can be equally responsible for stacked deltaic geometries (Kim & Jerolmack, 2008; Longhitano, 2008) and includes processes such as river meandering, channel avulsion, incision and lateral delta-lobe switching (Miall, 1996; Longhitano, 2008; Stouthamer & Berendsen, 2007). The latter is particularly common in deltaic systems and is becoming increasingly recognised as a principal process in the architectural development of deltas (e.g. Dorsey et al., 1997; Stouthamer & Berendsen, 2007; Longhitano, 2008). Furthermore, flume and numerical modelling of deltaic systems are progressively documenting the importance of alternating autocyclically-generated phases of erosion (channellized flow) and aggradation (sheet flow) in deltaic evolution (e.g. Van Dijk et al., 2008, Kim & Jerolmack, 2008; Van Dijk et al., 2009). However, these experiments assume constant allocyclic conditions such as subsidence, base level and sediment supply and are therefore only applicable to periods of relative quiescence in tectonic and climatic conditions. The consequence of such experiments has led to the reappraisal of deltaic successions previously considered to be allocyclically controlled. For example, Kim & Jerolmack (2008) provide alternative hypotheses with regard to studies by Collela (1988) and Dorsey et al. (1997). The latter indicate tectonic control on cyclic deposition, whilst Kim & Jerolmack (2008) suggest a well-reasoned autocyclic interpretation.

Isolating allo and autocyclic processes and their respective controls on sedimentation patterns is frequently challenging, since complicated modifying interactions between the controls exist (e.g. Yang et al., 1998; Cecil, 2003; Olariu & Bhattacharya, 2006; Stouthamer & Berendsen, 2007). However, a number of criteria can be used to help recognise their relative roles. This can be achieved by assessing: a) the temporal framework of the succession, b) the spatial distribution of the deposits and c) the internal sedimentary structures in successive cycles. Autocyclic and many allocyclic tectonic movements are for the most part episodic processes (Cecil, 2003; Kim & Jerolmack, 2008), distinct from climatic and glacio-eustatic variations which are frequently periodic, particularly if controlled by orbital forcing parameters as previously discussed in section 3.1. A good chronostratigraphic control on the depositional cycles is therefore essential for the critical appraisal of allo versus autocyclic controls. If age constraints are lacking, which is frequently the case in reworked or coarse-grained deltaic systems, the application of bounding surfaces to key stratigraphical horizons can provide a basic assessment of the timing involved (section 3.3). Spatially, allo and autocyclic deposition are separable by their physical scales and is probably the most useful technique for differentiating between the two controls. Parasequences/depositional cycles with limited lateral extent (locally developed) are controlled by processes which operate intrinsically within the basin and are therefore autocyclic in origin (e.g. Miall, 1996; Yang et al., 1998). Regionally extensive cycles on the other hand respond to larger scale allocyclic processes and are recognized on a basinal to global scale (Arnott, 1995; Miall, 1996; Yang et al., 1998). Lastly, sedimentary structures within the cycles can indicate the stability of the depositional system and record variations in depositional style throughout evolution of the delta. For example, if autocyclic control were to be attributed to the cyclic changes in sedimentation it may be expected that palaeocurrent directions would vary substantially from one depositional cycle to the next. This is in view of the fact that an alteration in the direction of input is required for the lateral shift of deltaic lobes to different depocentres (Dorsey et al., 1997; Postma, 2001; Longhitano, 2008).

The above review demonstrates that allo and autocyclic processes can individually produce cyclic repetition in sedimentary successions, however consideration should also be given to the combined effect of these controls (e.g. tectonic triggering of channel avulsion events; Miall, 1996, Stouthamer & Berendsen, 2007). By adhering to the above criteria and integrating regional information such as comparisons with contemporaneous systems in surrounding basins, distinguishing between the controls is potentially feasible.

3.6 Facies and Depositional Environments

A detailed sedimentological study of the Pissouri deposits has allowed a series of eight facies to be identified (Table 3.2), and are interpreted to have been deposited within three main generic depositional environments: a) delta front, b) lower delta plain and c) upper delta plain. These facies were identified to help determine parasequence packages and their subsequent correlation to the global sea level curve of Miller et al. (2005). Facies are depicted on the graphic log in Figure 3.4 with characteristic features summarised in Table 3.2 (located towards the end of this section).

3.6.1 Facies Association (A)

This facies association occurs in the basal part of the fan delta succession and comprises a bioclastic, pebbly and hummocky cross-stratified facies (A_1), a bioclastic massive sandstone facies (A_2) and a thick cross-bedded sandstone facies (A_3). These were all deposited in a deltaic setting and display a progression from marine through to marginal marine.

Facies A_1 – Bioclastic, carbonate cemented pebbly beds with hummocky cross-stratification

Description: This facies forms the basal component of the fan delta succession and consists of numerous beds, each of which is detailed in Table 3.2. The facies exhibits a minimum thickness of 3.0 m (contact between A_1 and the underlying formation not exposed), a minimum lateral continuity of ~ 300 m and is most likely comparable with the 'Bioclastic calcarenite' of Stow et al. (1995). The facies is characterized by thin (~20 cm), abundant pebbly bioclastic rich beds (Bed Type 1, Table 3.2), with each successive pebbly bioclastic layer slightly finer than the previous, resulting in an overall crudely graded fining upwards trend (Fig. 3.5a). The rounded to subrounded pebbles are primarily derived from the uplifted Troodos Massif to the north and are composed of ophiolitic lithics such as gabbro, diabase and basalt. These sharp-based beds are moderately to well sorted, clast supported and display a diverse array of predominantly articulated macro and microfossils (Table 3.2, Fig. 3.4f, Appendix G). Loading and flame structures are occasionally located at the base of the bed. A number of these layers occur randomly, exhibiting an erosive base, cutting into and interspersing with the poorly sorted, medium to coarse-grained sandstones of Bed Type 2. This latter bed type is defined by smaller fragments of bioclasts, a lack of pebbles, thicker beds (~30-40 cm) and an abundance of sedimentary structures such as hummocky and trough cross stratification, wave ripples (Figs. 3.6a, 6b) and herringbone cross stratification (rare). Thin section analysis of the pebbly hummocky layers reveals a dominance of well-preserved benthic foraminifera, including *Elphidium sp.* and the occasional *Nummulites sp*. (Loeblich & Tappan, 1988; Fig. 3.4f & Appendix G). Denoting the uppermost part of this facies is Bed Type 3 (Table 3.2), identified by thin 1-2 cm beds, which regularly alternate between very coarse and fine sandstone. Rare oyster shells occur at the base of the bed and a smooth weathered appearance is evident throughout.

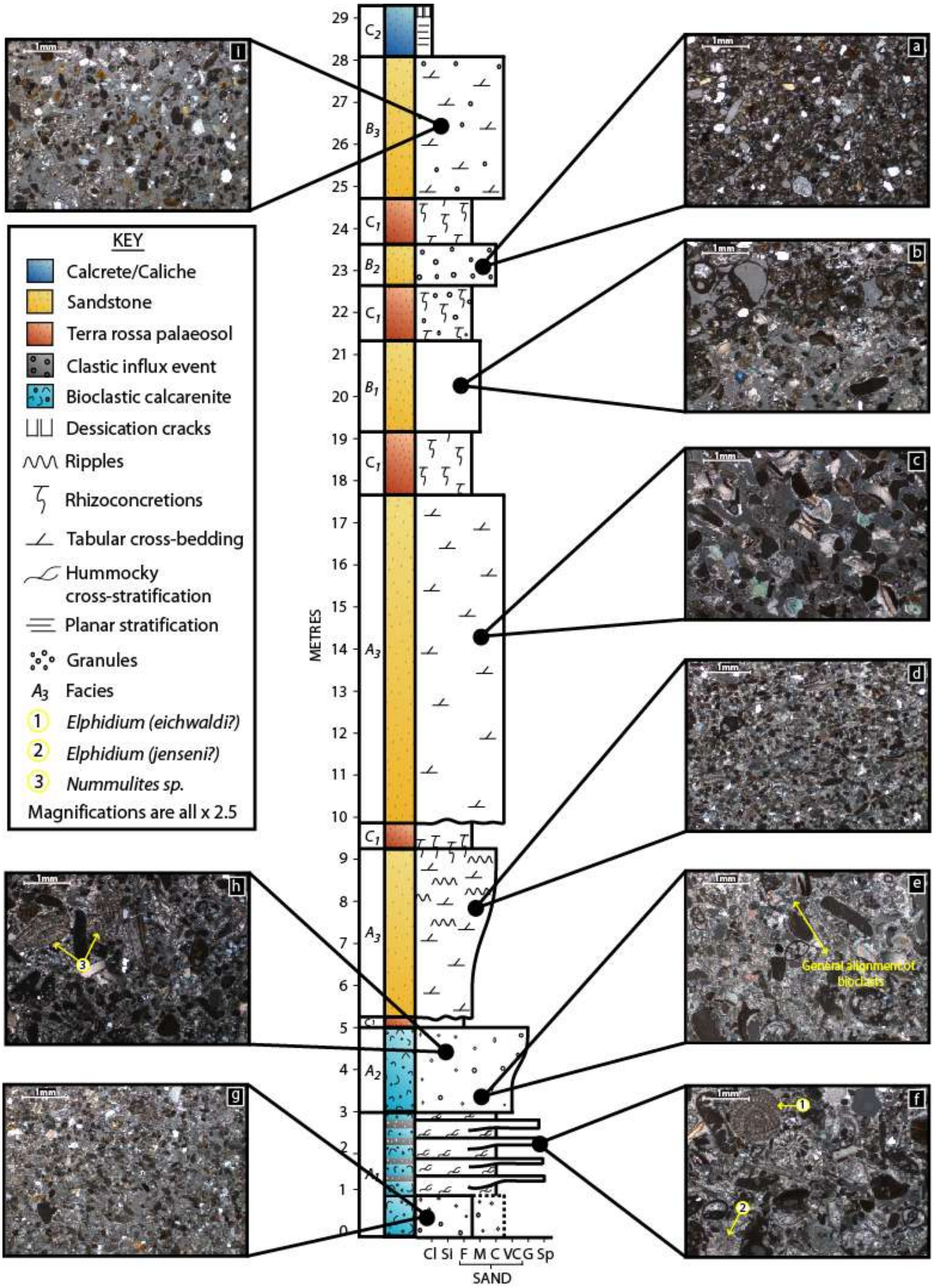


Figure 3.4 – Generalized stratigraphical log of the Pissouri Fan Delta. Facies are depicted with relevant thin section images

Interpretation: The presence of hummocky cross-stratification in the sandstones indicates deposition above the storm wave base (Cantalamessa & Di Celma, 2004) in the offshore transition zone and implies a frequency of storm events (George, 2000; Reading, 1996). The system has additionally been influenced by episodic tidal processes, indicated by the presence of rare herringbone cross-stratification (Martin et al., 2009). Overall this facies represents a characteristically high-energy environment with rapid deposition. Sharp, erosionally based bioclastic layers (Bed Type 1), which occasionally exhibit loading and flame structures provide the best evidence, and are attributed to a high frequency of coarse clastic input into the delta system. The crude fining upwards of each successive layer suggesting either i) a waning of clastic influx into the basin, ii) the preservation of successively more distal equivalents of each flow or alternatively, iii) the sharp based graded beds could be remnants of tempestites which have been episodically emplaced by storms, such as those identified by Breda et al. (2007) and Nielsen et al. (2006). The association of wave ripples, hummocky cross-stratification, swaley cross-stratification and tabular/trough cross-bedding suggest these are tempestites (Reading, 1996; Einsele et al., 1991; Molina et al., 1997). The occasional erosively based beds (sometimes containing wave ripples), which incise into the sandstones (Bed Type 2), may be due to minor channel erosion due to changes in the flow regime. Alternatively they may represent a ravinement lag, which has developed as a result of marine transgression, analogous features of which were described by Le Roux & Elgueta (1997) from paralic deposits in the Trihueco Formation, Chile.

The horizontally thin-bedded uppermost part of this facies (Bed Type 3) may indicate deposition in the foreshore, with the alternating coarse-fine layers representing periods of higher and lower energy conditions respectively, within the surf-breaker zone. The higher energy, coarser layers are most likely attributable to storms in the foreshore setting (Le Roux & Elgueta, 1997; George, 2000).

The presence of *Elphidium sp.* within this facies suggests a brackish, shallow marine environment with water depths no greater than 50 m (Murray, 2006). Dominance of this genus occurs in open lagoon or embayed coastal areas under the influence of freshwater input (Trincardi & Correggiari, 2000). However, these surprisingly intact benthic foraminifera are found within pebbly storm deposits above the storm wave base. These may have been transported from shallower environments during storm waning. Collectively the sediments within this facies document the

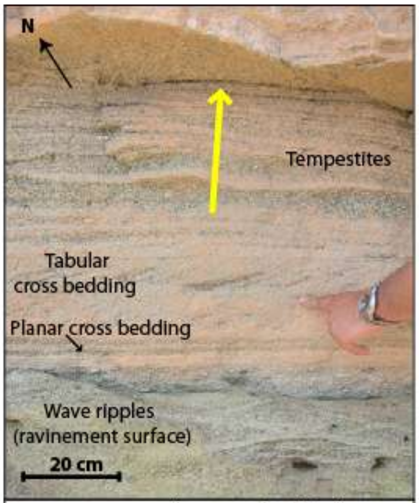


Fig. 3.5a - Fining & thinning of pebbly horizons

Fig. 3.5b - High angle cross bedding in channel

Fig. 3.5c - Concave nature of the channel bases

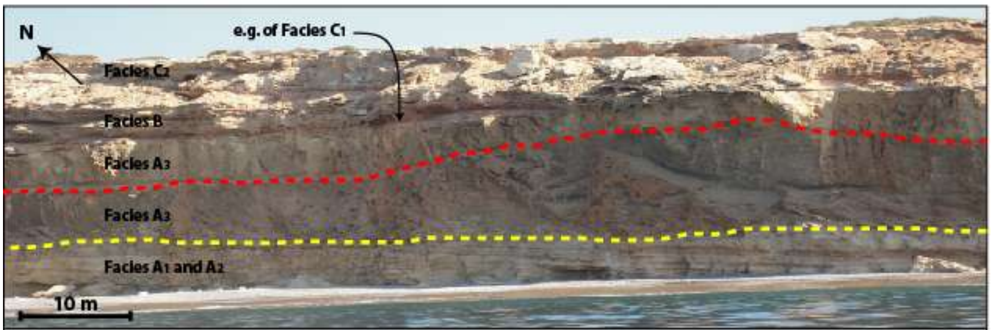


Fig. 3.5d - Clear distinction between parasequences 1 and 2 (delineated by yellow line). Erosional relief between Parasequences 2 and 3 (delineated by red line)

Fig. 3.5e - Highly undulatory nature of the palaeosol horizons (Facies C_1 - delineating sequence boundaries)

Figure 3.5 – Photographs of the key sedimentary structures in the Pissouri Fan Delta complex

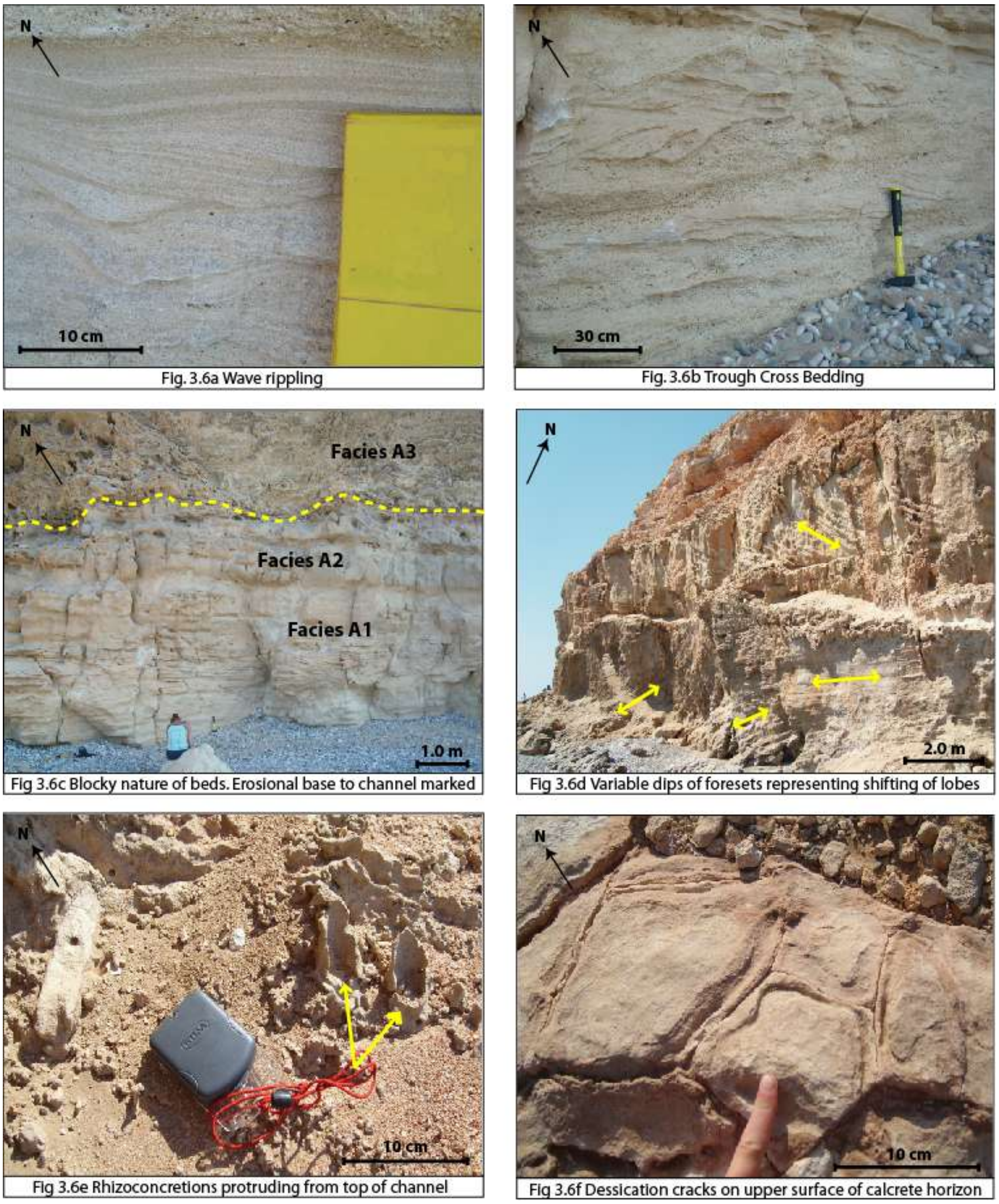


Figure 3.6 – Photographs of the key sedimentary structures in the Pissouri Fan Delta complex

evolution from offshore transition zone to foreshore in a medial to distal delta front setting and is typical of a storm and wave influenced delta. Analogous deposits and similar environments have been described from the Book Cliffs, Utah (Coe, 2005) and the modern deltaic lobes of the Ebro, Spain (Bhattacharya & Giosan, 2003).

Facies A_2 – Bioclastic calcarenitic beds

Description: This facies has a relatively planar and erosional basal contact with Facies A_1 (Fig. 3.5d & 3.6c), exhibits a maximum thickness of 4.0 m and lateral continuity of ~

300 m. The lowermost part of the facies is laminated, organised with a definitive alignment of the bioclasts (Fig. 3.4e &Appendix G). The uppermost part, however, is poorly sorted, with subrounded grains in a fine to coarse-grained matrix. Within the matrix there is an abundance of intact planktonic foraminifera and the dominance of the benthonic genera *Nummulites sp*. (Loeblich & Tappan, 1988; Fig. 3.4e & 3.4h). For the most part this facies contains similar bioclastic content to the underlying Facies A_1, although contains a slightly less diverse assemblage of foraminifera. The weathered nature of the beds gives a blocky, structureless appearance, however there is evidence for two or three poorly defined beds within this sequence. A distinguishing feature of this facies includes the random distribution of granules/pebbles throughout; this is in conjunction with a broadly coarsening upwards trend, increasing disorganization in grain sorting and thickening of the beds to the east-southeast. Syn-depositional growth faults and minor slumping are evident in places.

Interpretation: The internal structures identified within this facies and those of the underlying Facies A_1 are analogous to a shoreface origin, similar to the bioclastic sandstones in the Ventimiglia incised valley fill of northwest Italy (Breda et al., 2007). Such a succession is identified by the abundance of shell fragments, a relatively rhythmic mode of deposition (particularly in Facies A_1) and a general coarsening upwards into Facies A_2 (Fig. 3.4). The sandstones of the Ventimiglia similarly show an absence of internal organization and poor sorting, indicative of mass transport deposits. The random distribution of pebbles throughout may therefore imply deposition via weak debris flows (Breda et al., 2007). The transition from well organized to poorly sorted grain distribution indicates rapid deposition and an upward increase in energy within the environment (Tucker, 1991).

The *Nummulites sp.* identified within this facies are indicative of an environment with water depths no greater than 130 m, are associated with relatively warm conditions and inhabit lagoonal to inner shelf environments (Murray, 2006). These foraminifera have been relocated from their original habitat via weak debris flows. It is therefore interpreted that this facies represents a shallow marine, relatively high-energy environment in a medial to distal delta front setting. An interpretation further supported by the presence of syn-depositional growth faults and minor slumping, features frequently seen in this type of depositional setting (Postma, 1984; Heller & Dickinson, 1985).

Facies A_1 and A_2 have previously been identified as pro-deltaic deposits by Stow et al. (1995), however the lack of hemipelagic material and deposition above the storm wavebase renders a pro-delta interpretation unlikely. For example most pro-deltas particularly in the Mediterranean and Black Sea margins are characteristically composed of thick mud rich sediments (e.g. Trincardi & Syvitski, 2005).

Facies A_3 – Medium to coarse-grained, thick, cross-bedded sandstones

Description: This facies occurs in the mid part of the fan succession and forms a major component of the PFD. The beds thicken and thin considerably, revealing a concave upward profile in cross section (Fig. 3.5c) and form broad, laterally extensive sand bodies (up to ~ 670m), which pinch out in a west-northwest direction towards Pissouri Bay. The beds consist of moderately to poorly sorted, medium to coarse-grained sandstones and exhibit a thickness of up to 8.0 m. A distinctive characteristic of the facies is the high angle (18˚-38˚), large-scale planar cross-bedding (up to 8.0 m) which display an angular contact with the base of the bed (Fig. 3.5b & 3.6d). Palaeoflow deduced from the planar cross-beds indicate a predominant trend to the southeast, with minor internal variation (Fig. 3.6d), in accordance with Stow et al. (1995). High densities of vertical, tubular, 1-2 cm thick rhizoconcretions are preserved throughout this facies, occurring most commonly in the uppermost part (Fig. 3.6e). Subsidiary sedimentary structures include occasional rippling within the uppermost surface of the lower sand body and a broadly coarsening upward profile.

Internal differences between the upper and lower sand bodies are reflected in the bioclastic content, sorting and grain size whilst the only visible differences externally are related to colour and erosional relief. The lower sand body is less bioclastic, much better sorted and of finer grain size compared to the upper sand body (Fig. 3.4c, 3.4d & Appendix G). In addition the lower sand body exhibits a mid to pale grey hue and some erosional relief, whilst the upper sand body displays a distinctly orange/brown colouration and considerably more erosional relief than the lower (Fig. 3.5d & 3.5e).

Interpretation: The large high angle cross-bedding which typifies this facies may indicate either, i) deposition of micro-Gilbert foresets (Stow et al., 1995), ii) large alternate bar features (e.g. McCabe, 1977), iii) subaqueous sand dunes such as those in the Požega subdepression, eastern Croatia (Velić et al., 2000), North Island, New Zealand (Anastas et al., 1997) and North-Betic Strait (Martin et al., 2009) or, iv) distributary channels displaying downstream progradation towards the sea. I believe these large, high angle cross-bedded sandstones are most comparable to those of a relatively proximal micro-Gilbert delta e.g. Duksung fan delta, southeast Korea (Chough & Hwang, 1997), in agreement with Stow et al. (1995). A deduction primarily based upon the characteristic steep angle of the foresets and the broad lenticular cross-section. Bottomsets are not preserved due to the shallow depth of water and deposition occurred predominantly through avalanching (Colella, 1988; Calvo et al., 2000).

Within this facies there is much evidence of channel switching, which is suggestive of an autocyclically controlled braided system (García-Hidalgo et al., 2007; Stow et al., 1995), further supporting the implied high sedimentation load and flux passing through the system (Sinha & Friend, 1994; Vandenberghe, 1995; Huisink, 1999; Mol et al., 2000; Frostick & Jones, 2002). The rhizoconcretions, which penetrate through the sandstone foresets, are derived from the overlying palaeosol horizons (Facies C_1), which cap each succession of A_3. These rhizoconcretions were previously identified as *Macaronichus* burrows by Stow (2006). However, the distinctive concentric layered, calcium carbonate infill of the structure (Retallack, 2001), the tracing of the roots from the upper palaeosol horizon through the sands and the prevalence of rhizoconcretions in areas where the overlying palaeosol horizons are relatively thick and mature (Facies C_1), indicates that these features are calcified roots. Avalanching of the foresets suggests a high rate of progradation of the system and therefore very high sediment supply (Massari & Colella, 1988), whilst rippling towards the tops of channels suggests a diminution in flow conditions.

The transition from the lower to upper sand body is associated with a reduction in the organizational sorting of the grains, concomitant with an increase in both grain size and bioclastic content. Thus indicating a significant increase in energy within the depositional system. The contrast in colours between the two sand bodies is most likely related to the upper sand body containing a greater content of mafic Troodos-derived lithic material (Fig. 3.4c & Appendix G). The basal erosional relief of the upper sand body is a significant surface that could perhaps be the product of an erosional hiatus (Fig. 3.5d & 3.5e).

It is concluded that this facies represents a relatively high-energy micro-Gilbert style delta, where deposition took place in a proximal to medial delta front setting (see also Stow et al., 1995).

3.6.2 Facies Association (B)

This facies association comprises a structureless sandstone facies (B_1), a coarse fossil-rich sandstone facies (B_2) and a cross-bedded sandstone facies (B_3), which were deposited in a predominantly fluvial setting with periodic marginal marine influence. These facies constitute the mid to upper portions of the fan delta succession and represent the development of significantly thinner beds. The bioclastic nature of these sandstones and the deposits described in facies association (*A*) are likely to be derived from two sources: i) from erosion of uplifted Miocene carbonate reefal and bioclastic limestone beds of the Pakhna Formation and, ii) from nearby carbonate platform deposits (Stow et al., 1995). Two sources of bioclastic material is confirmed by the presence of both relatively complete examples of fossils and the occurrence of bioclastic detritus which has been clearly reworked (very fragmented, rounded and display diagenetic alteration), occurring within the same depositional packages (refer to Fig. 3.4a, b, i & Appendix G).

Facies B_1 – Medium-grained, moderately sorted, structureless sandstone

Description: This facies has a relatively planar basal contact, a total thickness of up to 3 m and has a lateral continuity of ~ 1300 m. The bed displays a mid-grey hue, consists of medium grained, moderately well sorted sandstones with subangular to subrounded grains. The facies is devoid of sedimentary structures and fossils, however thin section analysis reveals a (rare) bioclastic content (Fig. 3.4b & Appendix G). The bioclasts are predominantly diagenetically altered and disarticulated fossils such as bryozoa, gastropods and unidentifiable shells.

Interpretation: The preservation and diagenesis of the dominantly molluscan, disarticulated and rounded bioclastic content within this facies suggests reworking of material, derived from the erosion of fossiliferous Miocene strata exposed in the hinterland. A primary marine signature for this deposit can therefore be discounted. The internally featureless nature of the deposit suggests rapid deposition within the channel (Reading, 1996; Nichols & Cantrill, 2002; Collison et al., 2006) and could be analogous to the channel-like sandbodies (SMC) of Martin & Turner (1998). These deposits have been identified in braided river systems, which feed sediment to a delta and display the same basic sedimentology described in Facies B_1 (i.e. grainsize, sorting, featureless nature). The lack of a fining or coarsening upward trend may imply the channel filled as a result of flood event(s) (e.g. George 2000) and supports the interpretation of rapid deposition. An absence of primary marine fossils or sedimentary structures related to marine processes (e.g. wave reworking, herringbone cross-stratification) provides circumstantial support for this fluvial interpretation.

Facies B_2 – Coarse fossil-rich sandstone

Description: This facies displays a relatively planar contact with the underlying facies, has a total thickness of up to 1.0 m and a lateral continuity of ~ 1300 m. The bed is a medium to coarse-grained, moderately well sorted sandstone with subrounded grains and a pale grey hue. Granules are randomly distributed throughout this facies in addition to an abundance of 'complete' impressions of shells, while thin section analysis reveals a background fragmented highly bioclastic matrix (consisting of bivalves, gastropods, bryozoa, corals and foraminifera; Fig. 3.4a, Appendix G). The facies appears to be devoid of any sedimentary structures, but is badly weathered.

Interpretation: The greater fossil content within this facies may be due to episodic storm events that allowed sea water (and marine debris) to penetrate much further upstream (Reading, 1996). Alternatively a greater tidal range may have accompanied this period of deposition, although is unlikely due to the lack of sedimentary structures that typify tidal processes. The background highly fragmented bioclastic reworked material is likely to be derived from the Miocene beds as described above for Facies B_1. The lack of sedimentary features makes it difficult to define this facies into a specific depositional element; it is therefore tentatively interpreted to be a lower delta plain feeder channel, similar to Facies B_1 however, with a marine or marginal marine influence. The facies exhibits some of the features indicative of a distributary channel, although does not satisfy all of the criteria (e.g. Reading, 1996).

Facies B_3 – Medium-grained, moderately to well sorted, cross-bedded sandstone

Description: This facies has similarities with those depicted by Facies A_3. The main differences between them are: the basal contact for this facies is relatively planar whereas A_3 is erosional in nature, the bed thickness (average 4.0 m) and bioclastic content is much reduced as compared to A_3 (revealed by thin section analysis). In addition, Facies B_3 exhibits a minimal bioclast content and high diversity in lithoclastic material (Fig. 3.4i & Appendix G). The lateral continuity is the same as Facies B_1 and B_2.

Interpretation: Thin section analysis reveals this is a reworked deposit with reduced bioclastic content as compared to Troodos derived material. Sediment flux is interpreted to be high as signified by the steep angle of the foresets and their oblique contact with the basal surface of the bed (previously ascertained in section 3.6.1). Based on the above observations this facies is interpreted to be entirely fluvial in origin, either representing a distributary channel or fluvial feeder channel in the lower delta plain. The sedimentary features satisfy a number of the criteria required for the interpretation of a distributary channel, e.g. cross bedding, moderately to well sorted, medium sand, subangular to subrounded grains, unidirectional flow, topped by rootlets (Reading, 1996).

Facies B_1 to B_3 are overlain by facies C_1, which is described in section 3.6.3 below.

3.6.3 Facies Association (C)

This facies association is comprised of Terra Rossa palaeosols (C_1) and calcrete/caliche (C_2), deposited in an entirely terrestrial setting. The Terra Rossas are found overlying each of the previously described facies of (*A*) and (*B*), whilst the calcrete/caliche drapes the uppermost surface of the fan delta succession.

Facies C_1 – Red/brown, rhizoconcretion-rich palaeosols

Description: This facies displays a highly undulatory basal contact (Fig. 3.5e) and overlies each of the previously described facies, with the exception of A_1 and B_3. It forms broad expanses, laterally continuous for up to ~1300 m and is distinguished by a characteristic deep red/brown colouration. White, irregular mottling and abundant vertical, tubular structures are present throughout. These vertical tubes frequently exhibit an average diameter of ~1cm, occasionally attaining 4-8 cm. No other sedimentary structures are apparent, however a secondary feature of this facies is the frequency of rounded to subrounded Troodos Massif derived granules, which are non-uniformly distributed. Lower in the PFD succession, this facies appears to be incipient, however a notable progressive thickening is evident up section, with maximum thicknesses up to 1.3 m.

Interpretation: The white mottling and abundant vertical, tubular structures throughout this facies represent the preservation of calcrete nodules and rhizoconcretions (Retallack, 2001; Wright & Tucker, 1991). This facies as a whole exhibits diagnostic features of pedogenic formation and is interpreted as a palaeosol, based upon the deep red colour (acquired through the process of rubification; Retallack, 1997), the presence of calcrete nodules and a high density of rhizoconcretions throughout. The abundance of rhizoconcretions within the palaeosols indicates the area was once highly vegetated with relatively well-drained conditions (González et al., 2007). A number of specific horizons would be expected within a soil profile (see Retallack, 2001); however there appears to be a lack of any distinctive soil sublayers, presumably attributable to pedoturbation. Rubification and calcrete nodules reflect an environment that was open to repeated wetting and drying (e.g. Wright & Wilson, 1987). ‘Pedogenic reddening’ or rubification is a defining feature of Terra Rossa soils and is typical of Mediterranean type climates (Kraus, 1997; Durn, 2003) with marked seasonality, high annual rainfall, warm, humid temperatures and low sediment supply (Retallack, 1997; Widdowson, 1997; Pope & Wilkinson, 2005; González et al., 2007). Relatively stable tectonic conditions are required for the formation of palaeosols, as intense uplift would likely promote rapid erosion of the pedogenic horizon thus terminating pedogenesis (Retallack, 1997; Widdowson, 1997; Wang, 2003).

This facies could therefore represent the flat to subhorizontal terrestrial topsets, which denote the uppermost portion of a Gilbert type delta, in an upper delta plain setting (Stow et al., 1995; Longhitano, 2008). Alternatively the palaeosols could have formed during a period of reduced clastic input, during abandonment of the fan delta (e.g. Reading, 1996). This is an important facies, clearly depicted at regular intervals throughout the succession and represents punctuated, prolonged periods of dormancy allowing pedogenic profiles to evolve. The lateral extent of the deposits suggests these were important, repeated events across the whole of the fan delta surface.

Facies C_2 – Calcrete/Caliche

Description: This facies occurs as a distinctive stratigraphic unit that is found draping in an undulatory fashion over the uppermost surface of the fan delta complex. It extends for ~ 1300 m, exhibits a total thickness of 1.25 m and is characterised by a white colour and very fine grain size. Sedimentary features are difficult to identify due to the weathered nature of the deposits, however occasional laminations and rare dessication cracks are evident throughout (Fig. 3.6f).

Interpretation: This facies is interpreted as a calcrete/caliche pedogenic horizon and could be classified as a laminar calcrete (Netterberg, 1980; Goudie 1983), in development stage 4 (Machette, 1985). The facies formed as a result of long-term emergence of the fan delta. Calcretes form in arid or semi-arid climates with a strongly seasonal precipitation regime (Watts, 1980; Wright & Tucker, 1991; Candy et al., 2005), in conjunction with limited sedimentation and/or surface stabilisation (Alonso-Zarza et al., 1998). Desiccation cracks support the semi-arid interpretation whilst the cryptic laminar appearance may be due to root mat formation over indurated horizons, or at watertables. These features are likely to represent a floodplain deposit in perhaps an upper delta plain or alluvial fan setting (Wright et al., 1988; Miall, 1996).

Table 3.2 – Facies description and interpretation of depositional environments in the Pissouri Braided Fan Delta Complex

DEPOSITIONAL ENVIRONMENT	FACIES ASSOCIATIONS/ LITHOFACIES	DESCRIPTION	FOSSILISED FAUNA/FLORA	INTERPRETATION	SEDIMENT SUPPLY	ACCOMMODATION SPACE
Delta Front (A)	Bioclastic, carbonate cemented pebbly beds & Hummocky Cross Stratification (A_1)	Bed Type 1: • Bioclastic beds, SR - R, moderately to well sorted granules to small pebbles. • Occasional loading & flame structures located at base of the beds. Bed Type 2: • Poorly sorted, medium to coarse-grained sandstone. • Hummocky & trough cross stratification, wave ripples & rare bimodal (herringbone) cross stratified horizons. Bed Type 3: • Pale cream - brown colouration. • 1 - 2cm beds alternating between v.coarse & fine sandstone layers. • Smooth weathered appearance.	Bioclastic horizons :- • Thick shelled marine bivalves • Scaphopods • Gastropods • Bryozoa • Corals • Foraminifera • Echinoid Spines? Sandy horizons :- • Rare oyster shells at base of bed (Bed Type 3)	Bed Type 1: • Bioclastic layers could represent tempestites? High energy environment, rapid depostion. Bed Type 2: • Deposition above storm wavebase in offshore transition zone. Bed Type 3: • Laminated areas - foreshore Overall: • Shallow marine offshore transition zone to shoreface with episodic rare tidal influence & numerous storm events. • Medial to distal delta front setting	HIGH	FLUCTUATING to HIGH
	Bioclastic Calcarenite (A_2)	• Weathered nature may give the appearance of being blocky/massive/structureless. • Very bioclastic including pebbles & granules derived from the Troodos. • Pale white/buff colouration. • Small pebbles to granules, scattered throughout.	Same as (A_1)	• Shallow marine • Relatively high energy • Medial to distal delta front setting	HIGH	REDUCED
	Medium to coarse thick-bedded sandstones (A_3)	• Channelised medium - coarse cross-bedded sandstones, SR grains & moderately - poorly sorted. • Medium - pale grey colour changing to orange/brown up section. • High angle cross - bedding (18°-38°) • Occassional rippling - towards top of beds • Variable bioclastic content.	Bioclastic content (complete & fragmented - reworked) :- • Bivalves • Gastropods • Bryozoa • Brachiopods? • Corals • Foraminifera Features at base of channel :- • Calcretised tree trunks (possibly recent) Features throughout channel :- • Rhizoconcretions	• Relatively high energy Distributary Channel with large bar features OR • Micro-Gilbert foresets showing down-stream progradation towards sea. • Much evidence of channel switching.	HIGH	INITIALLY HIGH

Table 3.2 continued

DEPOSITIONAL ENVIRONMENT	FACIES ASSOCIATIONS	DESCRIPTION	FOSSILISED FAUNA/FLORA	INTERPRETATION	SEDIMENT SUPPLY	ACCOMMODATION SPACE
Upper to Lower delta plain transitional area (B)	Medium grained massive sandstone (B_1)	• Medium grained sandstone, SR-SA grains, moderately sorted • Mid-grey colouration • Massive, potentially amalgamated? • No obvious sedimentary structures	Bioclastic fragments :- (Reworked) • Bivalves • Gastropods • Array of unidentifiable shells	• Channel sandbody • Feeder channel to the main delta • Rapid deposition	HIGH	LOW
	Coarse fossil rich sandstone (B_2)	• Medium - coarse sandstone • Light grey colouration • Bioclastic • Granules distributed throughout. • Sedimentary structures not evident, however the section is badly weathered.	Bioclastic fragments :- (Reworked) • Bivalves • Gastropods • Abundance of imprints of articulated bivalves.	• Marine - marginal marine • Feeder channel to delta system OR • Distributary channel?	HIGH	LOW
	Medium grained, moderately to well sorted cross-bedded sandstone (B_3)	• Relatively planar basal contact • Similar in characteristics to (A_3) but with reduced bed thickness & bioclastic content & less well sorted • Very reworked • No definitive grading	Bioclastic fragments :- (Very reworked) • Gastropods • Foraminifera • Bryozoa? • Pollen spores?	• Distributary channel? OR • Main feeder channel to delta system	HIGH	LOW
Upper Delta Plain (C)	Terra rossa Palaeosols (C_1)	• Undulatory basal contact • Deep red/brown colouration • Fine - medium sand, SR - R grains, moderately - well sorted • Granules often distributed non uniformly throughout the horizon	• Medium - high abundance of rhizoconcretions • Average thicknesses of ~1cm however they can attain 4-8cm	• Humid climate • Seasonal, high rainfall • Limited runoff • Highly vegetated	LOW to ZERO	LOW to VERY LIMITED
	Calcrete/caliche (C_2)	• Dessication cracks evident on upper surfaces • Very fine grain size • White colouration • Sporadically laminated	None	• Semi-arid to arid climate • Strong seasonal precipitation • Surface stabilisation • Limited sedimentation	LOW to ZERO	LOW to VERY LIMITED

3.7 Synthesis and depositional model

Deposition occurred in a variety of calciclastic to clastic environments ranging from storm and wave influenced deltaic deposition of Facies A_1 and A_2 (delta front), superseded by fluvial influenced deltaic deposition of Facies A_3, facies associations *B* and *C* (delta front, lower and upper delta plain respectively). The notable thinning and increase in lateral extent of the uppermost Facies B_1, B_2 and B_3 may be related to unconfinement (related to accommodation), reduction in sediment supply or due to the duration of sedimentary accumulation, these are discussed further in section 3.8.

The temporal evolution of the PFD can be documented through the recognition of key regionally extensive surfaces that divide parasequences (e.g transgressive surfaces, maximum flooding surfaces and sequence boundaries). Parasequences are often defined as '*a relatively conformable succession of genetically related beds or bedsets bounded by flooding surfaces*' (Van Wagoner et al., 1990; Catuneanu et al., 2008). I however propose that the term 'parasequence' should include regionally significant metre-scale cycles, not necessarily delimited by flooding surfaces (Spence & Tucker, 2007; Catuneanu et al., 2008). Using this broader definition the PFD succession has been divided into six parasequences each divided by a sequence boundary (see below).

Parasequence 1

The base of this parasequence is not seen; nevertheless, the lowermost counterpart exhibits a shallowing trend from lower shoreface/offshore transition zone facies through to middle shoreface and foreshore deposits. Overlying this sequence is the return of lower shoreface/offshore transition zone facies which are subsequently replaced by a shallowing and coarsening upwards trend (Fig. 3.4). The parasequence exhibits typical characteristics of shoreface to foreshore deposits in a wave-dominated delta (Fig. 3.7).

The presence of numerous ravinement lags (Fig. 3.5a) is indicative of shoreface erosion during marine transgression (Le Roux & Elgueta, 1997; Siggerud et al., 2000; Clifton, 2003). These ravinement surfaces indicate accommodation being created (rising sea level) was greater than the flux of sediment to the system (Siggerud et al., 2000). The overlying depositional package depicted by a coarsening upwards bioclastic sandstone and weak debris flows is interpreted as a deposit of the progradational phase of a highstand systems tract (HST).

The collective shallowing and coarsening upwards succession depicted by Facies A_1 to A_2 in Parasequence 1 is indicative of a transgressive to highstand system tract comparable to the Book Cliffs, Utah (Coe, 2005). The top of this coarsening upwards package is overlain by a palaeosol deposited during a lowstand (LST) systems tract, the uppermost surface of which denotes a sequence boundary. The presence of a palaeosol is a reoccurring association seen in each parasequence.

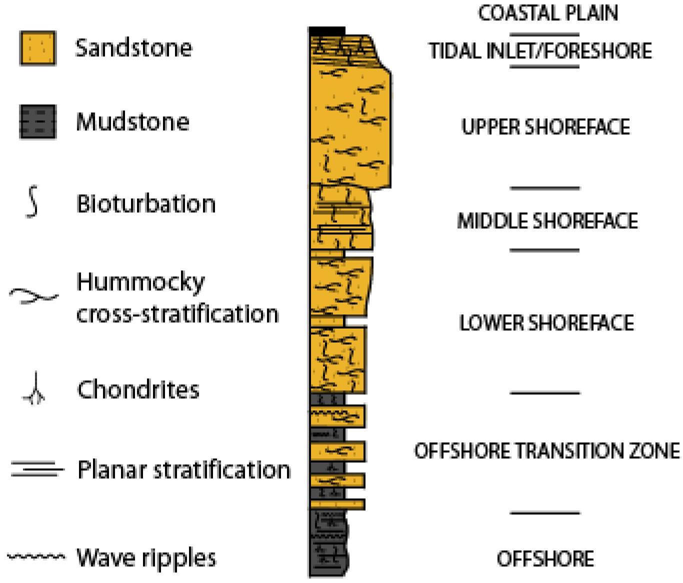


Figure 3.7 – Typical features of a wave influenced deltaic sequence (Coe, 2005)

Parasequence 2 and 3

These incomplete parasequences are each composed of an erosively based, large cross-bedded, thick channel, which in places broadly coarsens upwards. The channels are clearly identified by the steep Gilbert style foresets (refer to section 3.6.1, Facies A_3). The creation of accommodation is high, though less than the rate of sediment flux, reflected by, i) oversteepened foresets within the channels, suggesting avalanching and consequently very high sediment supply rate. The steepening of foreset slopes with increasing sediment input and grain size are frequently associated (Einsele, 1996), ii) oblique foresets, clinoform shape is often regarded as an indirect criterion for estimating the ratio of accommodation to supply (Helland-Hansen, 1993). The oblique foresets such as those in the Pissouri channels suggest high sediment supply in comparison to accommodation and are associated with sea level fall, particularly in settings of slowly decreasing accommodation (Massari et al., 1999). Such foresets have been recognised in prograding deltaic bodies during glacial lowstands in the Seyhan, Ceyhan and Tassus deltas, Turkey (Aksu et al., 1992) and the Crotone Basin, Southern Italy (Massari et al., 1999), and iii) the distinct lack of bioturbation could indicate high rates of sediment flux into the system concomitant with high-energy conditions, an environment clearly unsuitable for habitation by burrowers.

The increased and high sediment flux compared to the underlying Parasequence 1 could be attributed to tectonic movement and incision of the source or alternatively climatic controls such as enhanced precipitation. Many emphasise the role of tectonism in creating high sediment flux through deltaic systems (e.g. Goodbred & Kuehl, 2000; Goodbred et al., 2003; Breda et al., 2007). However, climate can be equally responsible and has been recognised as the predominant influence in areas such as the Loreto Basin, Mexico (Dorsey et al., 1997), the southern North Sea basin (Overeem et al., 2001) and the Crotone Basin, Italy (Massari et al., 2007). The cause of this influx is discussed further in section 3.7.1, where the relative roles of tectonics and climate are evaluated for this depositional timeframe.

These progradational parasequences are interpreted to be LST deposits, which shallow upwards into LST palaeosols. The palaeosols formed after the accommodation was infilled by the prograding fan delta. When sediment supply reduced, the delta became abandoned promoting the accumulation of Terra Rossa palaeosols in perhaps slightly warmer and seasonally wet climatic conditions.

Parasequences 4 to 6

These parasequences have a more fluvio-terrestrial signature (fluvial channels) and a much-reduced thickness compared to the underlying parasequences. Despite their depositional differences they still display a similar lithological pattern to the previous parasequences, i.e. a sandstone package overlain by a palaeosol (Facies C_1) in a shallowing upward trend. The thinner beds may be attributable to either, i) a reduction in the creation of accommodation and overall rapid infilling of the basin or, ii) reduced residence time for sediments to accumulate before the progradation phase. Allocation of sequence stratigraphical tracts to these deposits can be problematic, particularly with respect to Parasequence 4 (Facies B_1) where there is no obvious distinction of grain size changes and sedimentary features appear to be absent. The lack of structural and sedimentary features may be due to rapid deposition within the channel (Nichols & Cantrill, 2002; Reading, 1996), indicating a high sediment flux. Parasequence 5 (Facies

B_2) contains a marine or marginal marine signature, potentially conforming with well documented accounts of Mediterranean Pleistocene falling stage and lowstand (glacials) successions, when intensified storm mixing occurred (Massari et al., 1999). These events likely transported marine material further inland penetrating into the fluvial channels feeding the delta. Parasequence 6 (Facies B_3) displays high angle cross bedding within a medium to coarse sandstone matrix (similar to Parasequences 2 & 3 with the exception of the erosive base and thickness). Based upon the previous deductions of Parasequences 2 and 3, it is likely this sandstone package is representing a LST, with a relatively high sediment flux (as represented by the steep foresets and progradational nature of the deposit). The thinner bed denotes a much-reduced accommodation compared to Parasequences 2 and 3.

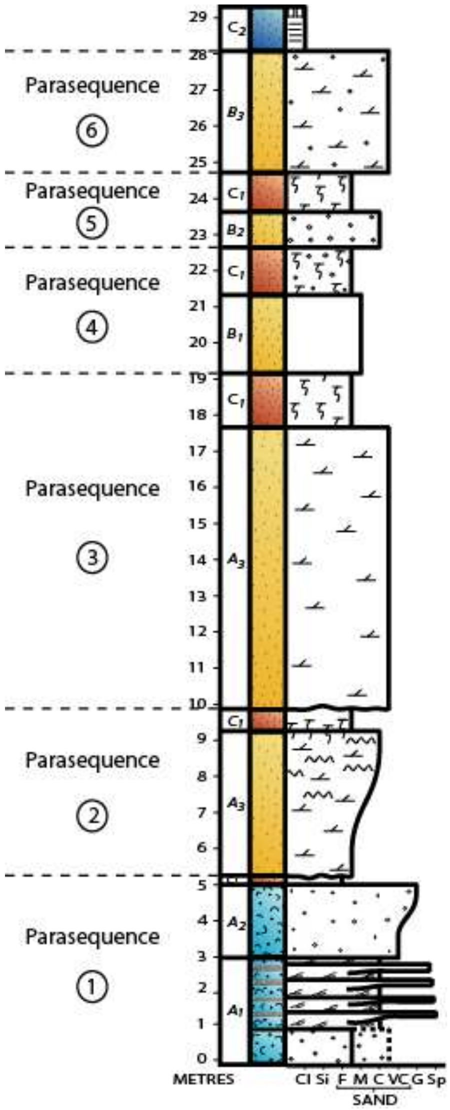


Figure 3.8 – Parasequence cycles within the Pissouri Fan Delta

3.7.1 Stratigraphical evolution of the PFD

Facies analysis has revealed that the succession initiated as a typical wave and storm dominated shoreface delta system at the base (Parasequence 1) and abruptly switched to a river/fluvial dominated regime (Parasequences 2 to 6), typified by the relatively thick marginal marine to fluvial channelised sandstones. This switch in depositional regime is consistent with an interpretation of a significant increase and constancy in sediment supply rate, whereby the river systems supplied sediment to the coast much faster than wave and tidal processes in the basin could redistribute it. For example the mixed influence Eridanos delta in the southern North Sea Basin (Overeem et al., 2001), which exhibits a comparable transition from wave to fluvial influenced sedimentation.

The switch to a higher sediment flux could be related to either, i) increased water supply in the form of precipitation in the drainage basin upstream or, ii) to tectonic uplift of the hinterland and subsequent incisional response of rivers. Variations in sediment load caused by either process in the hinterland can promptly induce such a change (Elliot, 1989). However, modifications in climate are now frequently regarded to be the principal controlling factor on sediment supply (Postma et al., 1993; Weltje & De Boer, 1993; Leeder et al., 1998). For example, Hovius (1998) devised empirically derived equations, which demonstrated that significant changes in sediment yield/supply could be accountable for by changes in climatic parameters such as runoff and temperature fluctuations. It may be argued that an increase in precipitation would contradict the notion of an increase in erosion and sediment supply, creating conditions conducive for dense vegetation growth, thus reducing effective runoff and the consequent delivery of sediment to the lower reaches of the basin. This may be the case for the majority of depositional systems as demonstrated by authors such as Owen et al. (1997); Leeder et al., (1998); Mack & Leeder (1999); Overeem et al. (2001); Macklin et al. (2002); Pope & Wilkinson (2005) and Pope et al. (2008). However, there are exceptions, as neatly demonstrated by Collier et al. (2000) who calculated increased sediment yields in Greece during wet glacials. Steppe vegetation prevailed with an absence of significant tree cover allowing high runoff and sediment delivery.

It is proposed that both climatic and tectonic processes influenced the switch in depositional regime from a wave to a river-dominated delta. It is envisaged that the combined effect of increased runoff from precipitation and the creation of erosional relief via uplift induced a sediment load effective enough to promote a switch.

Thereafter sediment flux is related primarily to precipitation effects based upon the lack of tectonic signatures within the deposits.

Notable thickening of the palaeosols, thinning of the sandstone channels and an increase in terrestrial influence up section is a feature indicative of an infilling basin during a period of long term sea level fall and/or no new accommodation. Palaeosols represent periods of tectonic inactivity (Retallack, 1997; Widdowson, 1997; Wang, 2003) and the thickening of the horizons up section may be suggestive of the successively longer periods of stability. In addition to this, the presence of terrestrial topsets (represented by palaeosols) overlying the fluvio-deltaic deposits inevitably suggests there was very limited to no accommodation being created, due to their entirely terrestrial nature and deposition considerably above sea level. It is plausible that the sandstone channels thin either due to, i) unconfinement due to a paucity of available accommodation, ii) a reduction in sediment supply or, iii) a reduction in the build up time for sediment accumulation between successive depositional events (Section 3.7.3). It is unlikely to be due to a reduction in sediment supply as the foreset arrangement within Parasequence 6 indicates a high sediment supply, it is therefore hypothesised that a long term lowering of sea level reduced the accommodation available.

3.7.2 Comparison of the Pissouri Fan Delta (Pissouri Basin) to the coeval debrites in the Khirokitia-Psemantismenos Basin

The coarse-grained debris flows and interlayered fine-grained deposits at Khirokitia (Fig. 3.2 and 3.9) exhibit the same number of fining upward parasequence cycles as the PFD. Davies (2001) documented six debris flow events, with the debrites interpreted as LST periods and the fine-grained material overlying each debrite interpreted to be TST/HST phases. Each flow is bounded by a sequence boundary. The Khirokitia succession (KDF) is fed by a point source (Davies, 2001), similar to the PFD (Stow et al., 1995), although differs in its basin geometry and proximity to the Troodos Massif (closer). The debris flows are considered to represent a high-energy system, with a considerable sediment flux, testified by the transport of clasts up to 2 m in diameter.

The maximum age of deposition for this sequence is much debated, however analysis from this study (Chapter 2) and others, indicate a late Pliocene to early Pleistocene age (Houghton et al., 1990; Davies, 2001). Deposition of the KDF therefore instigated at a comparable timeframe to the PFD. An additional minimum age constraint for this locality is provided by the nannoplankton *P. indooceanica* (NN20; Perch-Nielsen, 1989). This was identified in the chalky, fine-grained matrix of the uppermost flow event, thus placing the final depositional event within a mid to late Pleistocene timeframe (<0.46 mya).

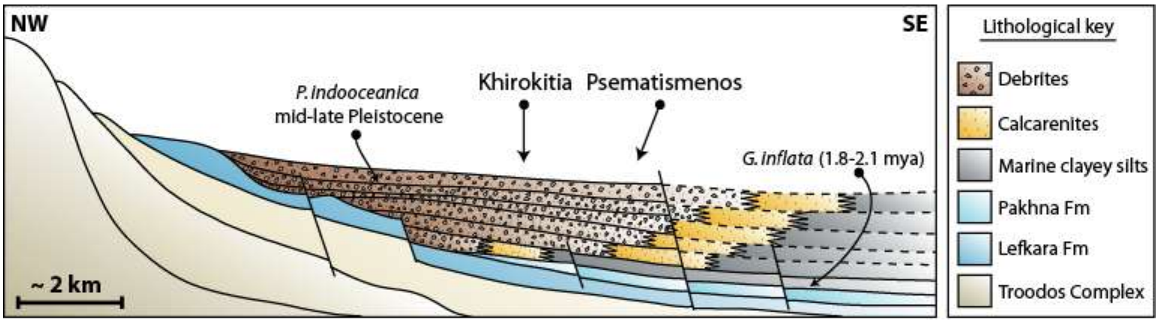


Figure 3.9 – Cross-sectional representation of the Khirokitia debris flows (adapted from Davies, 2001)

In the PFD the groupings of facies associations into parasequences reflect a repetitive stacking of LSTs in an evolving progradational/regressive and shallowing, wave to fluvio-deltaic system, set against a background long-term sea level drop (regression). The KDF succession similarly reveals a progradational sequence and the preferential preservation of LST deposits, although includes the poor development of hemipelagic TST/HST sediments, deposited when the fan became abandoned. It is therefore considered that these successions share a similar depositional history.

3.7.3 Temporal evolution - correlation with the global eustatic sea level curve

If the global eustatic sea level curve of Miller et al. (2005) is compared to the depositional timeframe for the PFD and KDF successions (maximum age of ~1.8 to 2.1 mya, minimum of ~0.46 mya) it can be seen that this is a period influenced by an overall lowering of sea level, punctuated by numerous glacial maxima (refer to Fig. 3.1). This is in congruence with the proposed progradational/regressional nature of the PFD and KDF deposits and the dominance of LST deposits, which was devised through the sequence stratigraphical analysis in previous sections. These glacial maxima or periods of relative lowstand could therefore hypothetically correlate with the sandstone/palaeosol and debrite parasequences of the fan successions.

A general correlation between the sequence stratigraphical interpretation and the global eustatic sea level is presented in Figure 3.10. Employing a systematic ‘top down’ approach and with the knowledge of the maximum age of the final parasequence, the fluvio-deltaic LSTs of Parasequences 2-6 can be correlated to glacial marine isotope stages (MIS) 22, 18, 16, 14 and 12 respectively. The parasequences occur on periodicities of ~90-150 kyr, corresponding to a 4th order high frequency sea-level control on a general short eccentricity periodicity. The systematic correlation with the sea level oscillations therefore suggests climate in the form of orbital forcing (Milankovitch cyclicity) as the primary control on the depositional architecture and cyclicity of the PFD and KDF successions.

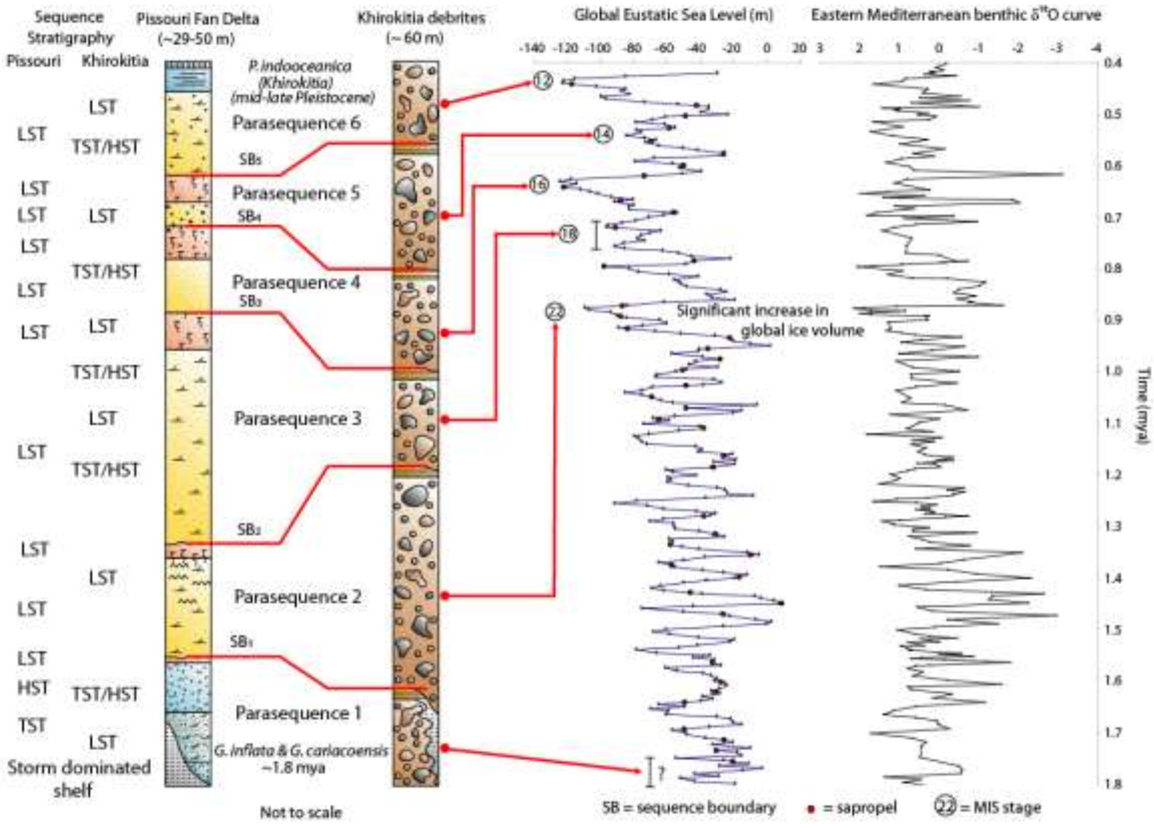


Figure 3.10 – Correlation of the sequence stratigraphical interpretation of PFD and KDF to the global eustatic sea level curve. Note: interpretation differs to Davies (2001)

This climatic deduction is further strengthened through the correlation of offshore sapropels to the onshore fan successions. These deposits only form during climatically wetter phases (refer to Chapter 4), usually during interglacial to interstadial warm periods (Bar-Matthews et al., 2000; Kallel et al., 2000), although there are exceptions e.g. glacial sapropels S6 and S8 (Cheddadi & Rossignol-Strick, 1995; Kallel et al., 2000). The glacial sapropels should therefore correspond to the sandstone and debrite channels, which have been related to periods of high sediment supply and runoff, this is confirmed on Figure 3.10. In conclusion, Parasequences 2 to 6 are implied to show climate driven fluctuations in supply, related to regional precipitation influence and to globally eustatic variations related to global ice volume. However, the above interpretation does not include Parasequence 1, which has an inferred age of ~1.8 mya. It is hypothesized that this parasequence may be a precursor to the initiation of main PFD/KDF sedimentation (in agreement with Davies, 2001). This theory, however, leaves a gap in the sedimentary record and is discussed below.

Early tectonic uplift of the Troodos Massif in the late Pliocene to early Pleistocene is well documented (e.g. Houghton et al, 1990; Robertson, 1998) and it is considered that the deposits of Parasequence 1 (~1.8 mya) are the product of this initial uplift (in agreement with Stow et al., 1995; Davies, 2001). Furthermore, rapid tectonic uplift occurred ca. 1.5 mya and was sustained until ca. 1.0 mya (Poole & Robertson, 1991; Spezzaferri & Tamburini, 2007). There is a strong possibility that this uplift event had an influence on the lower part of the PFD/KDF sedimentation. It is likely to have promoted the increase in sediment flux (erodable relief created), and induced the switch in PFD from a wave and storm influenced marine fan (Parasequence 1) to marginal marine/fluvial deposition (Parasequences 2 to 6). A transition from storm dominated shelfal conditions in the distal parts of KDF (Parasequence 1) to an overlying major progradational debris flow unit (Parasequence 2) shows comparable evidence. The gap in sedimentation between Parasequence 1 and 2 is thus considered to be tectonic in origin. This is supported by the first appearance of ultramafic material (including serpentinised grains) within Parasequence 2 at Pissouri (Stow et al., 1995), indicating uplift and exposure of the plutonic and mantle sequences. During the rapid tectonic uplift it in inferred that sediment by-pass occurred, thus explaining the gap in sedimentation (e.g. Coe, 2005). When the rate of tectonic uplift diminished (~1.0 mya; Robertson, 2000) the significant magnitudes of the middle to late Pleistocene sea level changes became the dominant control on sedimentary sequences. Sea level rises occurred at an average rate of ~10 m/ka^{-1} and fell at an average rate of ~1.5 m/ka^{-1}, with ~80% of time spent in eustatic fall (Cantalamessa & Di Celma, 2004). The reduced rate of tectonic uplift in Cyprus during this period has not yet been quantified, although is unlikely to have exceeded the rates of sea level change, therefore the variances in Pleistocene eustatic sea-level changes always outpaced any tectonic movement (e.g. Piper & Perissoratis, 1991). The Pleistocene high frequency parasequences must therefore be of glacio-eustatic origin. In addition the sequence boundaries described in the PFD/KDF successions can be correlated with some degree of confidence to sequence boundaries throughout the Mediterranean and as far a field as the Gulf of Mexico (Haq et al., 1987; Catalano et al., 1998; Hardenbol et al., 1998). Though a complete record is not recorded in each section, the correlation supports global eustacy (plus runoff related to changes in rainfall) as the predominant control on sedimentation.

3.8 Discussion

The PFD and KDF provide a cyclic record of sediment accumulation throughout the mid to late Pleistocene. It was originally predicted that the sedimentary cycles would correlate with glacio-eustatically driven sea level changes on the 3rd to 4th orders (Vail et al., 1991; Lourens & Hilgen, 1997; Chiocci, 2000), if they were climatically controlled. Consideration of the climatic conditions during the timeframe of deposition led to the hypothesis that the successions would be dominated by falling stage or lowstand deposits with a minor highstand or transgressive component. These hypotheses are now considered to be applicable to the PFD and KDF successions, given the approach adopted in this study.

Sequence stratigraphical analysis identified only one transgressive systems tract and no transgressive surfaces in PFD, whilst thin deposits of TSTs have been inferred in the KDF succession (Davies, 2001). The lack of or limited thickness of these deposits could be related to switches from high sediment flux (sandstones and debrites of the LST) to a very low sediment supply (e.g. Trincardi & Correggiari, 2000). If the sedimentary system does not have a fast enough response time to keep up with a rise in sea level then no sediments will be deposited. This is a situation, which would be expected in the mid to late Pleistocene, where deglaciations (sea level rise) were rapid and glaciations (sea level drop) were long lived (e.g. Maslin & Ridgwell, 2005; Miller et al., 2005). Short-term small-scale transgressions would therefore have occurred (Coe, 2005), but preservation of the deposits would be limited to absent, due to subsequent erosion of what would have been a relatively thin sedimentary package. Sequence stratigraphical analysis of the deposits suggests that overall LSTs expressed as prograding fluvio-deltaic sandstones (overlain by thinner deposits in the form of rhizoconcretion rich Terra Rossa palaeosols, PFD) and debrites (KDF) have been preserved. Each parasequence is bounded by a sequence boundary and is an interpretation that is consistent with the wider Mediterranean Pleistocene sedimentary record (Section 3.8.1).

It may be argued that the sequence boundaries (SB) proposed in this study would be better considered as maximum flooding surfaces (MFS) in a parasequence set (LST sequence), particularly if referring to the traditional parasequence definition mentioned previously in section 3.7. It may therefore be suggested that the SB should be placed at the base of the succession. This interpretation is debatable considering no identifiable features of a MFS are present, for instance: i) condensed, 'base of parasequence' shell beds. These beds frequently build up during times of initial marine flooding in siliciclastic dominated regimes (Shanley & McCabe, 1994; Brett, 1995; Coe, 2005), ii) thin brackish/marine sediments in an extensive landward position (Coe, 2005) or iii) nodules indicative of a pause or decrease in the rate of deposition (Coe, 2005).

SBs tend to form during sea level fall (e.g. Posamentier & Vail, 1988; Strasser et al., 1999) and in paralic successions is recorded by a basinward shift in facies belts (evident in the PFD and KDF). The SB reflects a hiatus and in places the surfaces show evidence of subaerial and/or submarine erosion (Shanley & McCabe, 1994; Arnott, 1995; Emery & Myers 1996). The maximal fall in the PFD is represented by the laterally extensive, subaerial palaeosols which can be regarded as significant and in places erosional stratigraphical hiatuses (an unconformity), they are therefore considered to represent the non-marine portion of a SB. Using biostratigraphical tie points the inferred correlations in Figure 3.10 indicate a correspondence with SBs across the Mediterranean basin (section 3.7.3) and support the interpretation. While valley incision would be unequivocal evidence for a SB (e.g. Shanley & McCabe, 1994; Emery & Myers 1996) it was unfortunately not possible to confirm due to the poor inaccessibility and traceability of the beds inland. However, erosive contacts are particularly evident in the earlier parasequences and may be evidence of valley incision. It is postulated that the upper sandstone beds do not demonstrate such an erosive contact perhaps due to their distance from the main channel.

It is acknowledged that a number of interpretations could be proposed for the studied sections, especially given the very incomplete nature of the parasequences/depositional cycles and restricted number of biostratigraphical tie points. Catuneanu et al. (2008) very aptly states 'the assignment of a SB to a stratigraphical surface is frequently at the discretion of the individual', and in this instance SBs rather than MFSs are favoured for the reasons stated above. Consideration of the depositional timescales of the cycles could be used to strengthen the interpretations (i.e. parasequence and MFS interpretation Vs sequence and SB interpretation) however a large amount of variation exists in the literature. For example, Burns et al. (1997) identifies sequences with thicknesses of 8-20 m on a 5th order scale (100-10 kyr) with SBs defined by palaeosols or channel scours. Aksu et al. (1992) similarly identifies depositional sequences on the 5th order timescale in deltas across Turkey, whilst Shanley & McCabe (1994) suggest sequences can span time periods ranging from a few thousand years to millions of years. Coe (2005) on the other hand suggests parasequences should occur on a high frequency (4th to 5th order), whilst sequences are of a lower frequency (2nd to 3rd order), in agreement with Brett (1995). The latter is the methodology originally followed in the interpretation of the PFD and KDF. However, consideration of the interpretations of Burns et al. (1997) and Aksu et al. (1992) indicates the cycles described in this study could be regarded as very incomplete sequences rather than parasequences, potentially corresponding better with the SB analogy. Due to the inconsistency in the literature the term 'depositional cycle' may be a more appropriate terminology to use?

3.8.1 Climatic and depositional trends within Pleistocene successions of the Mediterranean

It is widely recognised that river systems responded significantly to enhanced climatic deterioration and to the duration of the climatic events during the MPT. This is most notable in mid-latitudes such as Europe, where a marked increase in incisional cycles in river systems began during the interval of 1.2-0.8 ma (Head & Gibbard, 2005). During the late Pliocene to Pleistocene Mediterranean falling stage to lowstand deposits are dominantly bioclastic in nature (Massari et al., 1999), a comparable and distinctive feature of the PFD and coeval deposits in the vicinity e.g. Amathus (Houghton et al., 1990; Robertson, 1998).

The Nile delta to the south of Cyprus formed coevally with the PFD/KDF successions, with main advancement phases during glacial lowstands (Sestini, 1989). The increase in supply of sediment through rivers and subsequent progradation of deltas (or coastal prograding bodies) has been related to pluvial conditions during Pleistocene glacials e.g. the Cadiz margin, Spain (Maldonado & Nelson, 1999) and the Seyhan, Ceyhan, Tarsus, Göksu deltas in the eastern Mediterranean (Aksu et al., 1992). Studies of mammals in Italy by Palombo et al. (2005) corroborate the above interpretations revealing that open arid conditions prevailed in the late early Pleistocene followed by a wetter and much cooler climate in the early middle Pleistocene. A similar pattern identified by Dupont et al. (2001) further afield in equatorial Africa (glacials cool and humid, interglacials warm and dry). The documented increase in precipitation in the early Pleistocene to mid Pleistocene glacials is considered to be a phenomenon specific to the central and eastern Mediterranean, as revealed by pollen records in Crotone, Italy (Joannin et al., 2007). A similar study by Massari et al. (2007), in the same vicinity indicates ‘wet’ glacials occurred between MIS 12-20 (glacials thereafter were arid), thus conforming with the sapropel occurrences and correlations made with the LSTs in Figure 3.10. In addition, cooling and increased precipitation has been shown to promote the formation of braided rivers (Vandenberghe, 1993; Mol et al., 2000); it would therefore be expected to see braiding during the glacial periods in the Pleistocene. Sandstone bodies in the PFD show significant evidence of this and corroborate with the observations of Vandenberghe (1993).

It has been demonstrated that the oldest prograding bodies of the Crotone Basin represent 4th order long-lived sea level falls and correlate to the major climatic transition at MIS 25 to MIS 22-24 and to MIS 18.2 (Massari et al., 1999), an interpretation coincident with the proposed ‘rejuvenation’ in the PFD and KDF deposits (Fig. 3.10). The glacial MIS 22 represents a significant turning point in the global climatic regime; it is associated with the first prominent Pleistocene glacio-eustatic lowstand (Muttoni et al., 2003) and corresponds to the start of the MPT. It is thought to have initiated major deltaic progradation in the Mediterranean inducing climatic de-vegetation, lowering of sea level and promoting conditions for substantial erosion. For example, it has been documented that a tenfold increase in sedimentation rate occurred in the Venice area whilst in the Bengal fan denudation rates and sediment fluxes increased significantly (Muttoni et al., 2003). This may partly explain why the parasequence correlated with MIS 22 in the PFD/KDF successions is relatively thick.

Through sequence stratigraphical and biostratigraphical analysis of the deposits it is therefore proposed that the cyclic stacking pattern of the parasequence packages is related to a systematic control such as climatic perturbations, most likely in the form of glacio-eustatic sea level changes. The repetitive, regular style of deposition from one parasequence to the next would not be expected with a tectonic analogy (e.g. Massari et al., 2007), however studies invoking fault-related control on repetitive stacking of deltas are evident in the literature. For instance, large-scale episodic fault slip events and clustering of earthquakes are considered to have induced repetitive deltaic (Gilbert-type) deposition in the Crati Basin, Italy (Colella, 1988) and the Loreto Basin, Mexico (Dorsey et al., 1997) respectively. However, as previously discussed in section 3.5, alternative theories disregarding a tectonic control have been proposed for the cyclic deposition in the aforementioned basins. The infill of the Pissouri Basin has previously been related to the uplift of the Troodos Massif with glacio-eustatic effects exerting a secondary modulating effect (Poole & Robertson, 1991; Stow et al., 1995). Stow et al. (1995) advocated significant sediment influx was controlled primarily by intense (pulsed) uplift of the Troodos and suggest rapid erosion during main pluvial periods of the Pleistocene. Whilst this study is in agreement with the sediment flux associated with enhanced periods of precipitation, there is no evidence to suggest the influx is attributable to uplift. The lack of evidence within the succession supporting a tectonic origin such as an abundance of syn-depositional faulting, deformation structures, angular unconformities or abrupt deepening/shallowing (e.g. Fernández & Guerra-Merchán, 1996; Coe, 2005) would indicate a preference towards the alternative theory of eustatic and climatic control suggested in this study. Although Stow et al. (1995) suggest the PFD had not been influenced by high frequency sea level fluctuations, the application of sequence stratigraphical analysis to these deposits and subsequent correlation to the global eustatic sea level curve in this study suggests otherwise. The parasequences correspond with major glacial events (MIS 22-12 for Parasequences 2 to 6) on 4th order, climatic, short eccentricity periodicity (~100 kyr) and are therefore high frequency in nature.

To conclude, the fan complex was deposited during a climatically transient phase, primarily influenced by fluctuations in the Northern Hemisphere Ice Sheets and the Mid Pleistocene Transition, whereby eccentricity became the dominant mode of climatic control (Lourens & Hilgen, 1997; Rohling & Thunell, 1999; van Vugt et al., 2001). This interpretation robustly correlates with the surrounding regional Pleistocene deposits i.e. volumetrically dominated by falling stage and lowstand deposits (Massari et al., 1999) with minimal highstand and transgressive preservation.

3.9 Conclusions

The PFD has now been established (this study) to have existed from ~1.8 mya to ~0.42 mya. The cyclical stratal packages within the succession developed in response to climatically induced sea level change and sediment flux, whilst tectonics created a second order control, creating enough relief to partially control sediment generation (uplift between ~1.5 to 1.0 mya). The overall shallowing upwards progradational trend in the fluvio-deltaic deposits and the presence of proximal lithofacies overlying distal lithofacies, indicate the Pissouri Basin was infilled through time by a series of small river dominated and braided lobate fan deltas, during an overall regression in sea level. A comparable depositional pattern has been identified in coeval deposits within the Khirokitia-Psemantismenos Basin, although exhibited in a more proximal facies (KDF).

In this study, the evolving sedimentary architecture of the PFD (and KDF) is interpreted to be a response to Pleistocene glacial maxima (Parasequence 2-6). Sequence stratigraphical analysis has revealed the preferential preservation of LST deposits within a long-term regressive system. The systematic correlation of the parasequences with the sea level oscillations suggests orbital forcing on a short eccentricity scale, as the primary control on the internal stratigraphic cyclicity of the successions. During these glacial maxima the eastern Mediterranean experienced cool, wet climates, thus indicating enhanced precipitation as the cause of increased sediment influx. The identified parasequences are therefore climatically controlled by the continuing expansion of the NHIS and cyclicity imposed post the MPT, conforming to depositional patterns in analogous Mediterranean wide Pleistocene sedimentary successions.

Chapter 4

Climatic controls on late Pleistocene alluvial fans, Cyprus

Acknowledgement note: This chapter has been submitted and accepted to the journal Geomorphology (Special Publication) for publication with Dr. S.J. Jones and Dr. H.A. Armstrong as co-authors. Jones and Armstrong both provided guidance and contributed suggestions and comments on the structure of the manuscript.

Abstract

Alluvial fans are commonly associated with tectonically active mountain ranges and tectonism is frequently held responsible for abrupt coarsening and cyclical sedimentation of alluvial fan sequences. Whilst it is accepted that tectonism provides the opportunity for alluvial fan development through the creation of topography, increasing gradients of fluvial systems supplying sediments, and creating accommodation for the storage of sediment flux, the role of climate in fan development is frequently neglected. The hypothesis that climatically controlled events can produce recognisable sedimentary signatures in alluvial fan deposits is tested in the active supra-subduction zone setting of the late Pleistocene of southern Cyprus. This study demonstrates through architectural analysis and the reconstruction of palaeoflood hydrology a recorded pattern of increasing and decreasing palaeoflow dynamics, with switches from a wetter to drier mode, clearly exhibited by changes in the sedimentology of the fan.

At the present day Cyprus has a semi-arid climate and is influenced by a strongly seasonal rainfall pattern, with precipitation largely restricted to the winter months and rare occurrences of summer cyclones. However at precession minima (minima in the precession index) increased activity of western Mediterranean depressions produces wetter summers. Using inference I propose that longer-term increases in rainfall increased river discharge as recorded in the fan palaeoflood hydrology and occurred at minima in the precession. These periods correlate with the deposition of conglomeratic channels and open framework gravels. Drier periods are exhibited by sandier braided

fluvial deposits. Shorter term or seasonal change is recorded in the form of 2nd and 3rd low order bounding surfaces.

This increased activity of Mediterranean summer depressions increased precipitation to the wider Levantine area and was coincident with increased intensity of the North African and Indian Ocean (SW) monsoons. The resultant increase in river discharges at precession minima from both the Nile (and the wider Levant) resulted in the formation of sapropels in the eastern Mediterranean and is recorded as wet periods in speleothem deposits in the Soreq and Peqiin Caves of Israel. Based upon the data and the correlations presented in this study, it is therefore considered the predominant control of sedimentation on the late Pleistocene alluvial fans of southern Cyprus was most likely climatically driven.

4.1 Introduction

The relative roles of tectonism, eustacy and climate are recognized as the primary controls governing landscape evolution, erosion of orogenic belts and sedimentation. Tectonism through uplift and creation of topography provides the increased energy necessary for fluvial systems to incise and erode (Frostick & Steel, 1993; Jones, 2002). Earthquake activity associated with major tectonic events particularly in mountainous regions can cause destabilisation and trigger landslides, generating increased sediment flux to drainage systems (e.g. Allen & Hovius, 1998; Dadson et al., 2004). Eustatic base level (tectonically and/or climatically controlled) governs whether a system incises or aggrades. Models conventionally suggest that sea-level fall is associated with incision, floodplain abandonment and terrace formation, with sea-level rise promoting aggradation (e.g. Posamentier & Vail, 1988; Koss et al., 1994; Harvey, 2002). Climate in comparison controls the temporal and spatial erosional processes (e.g. rivers), the release of sediment from the catchment and the vegetative cover that protects the landscape from erosion and denudation (Thamó-Bozsó et al., 2002; Pope & Wilkinson, 2005; Weissman et al., 2005). Climatically controlled changes of palaeohydrology and catchments can exert an important influence on sediment generation, transportation and preservation (e.g. Jones & Frostick, 2008). Furthermore climate has been shown to have significant importance in governing large flood events that can substantially modify landscapes and existing fluvial networks (Molnar et al., 2006).

Alluvial fans are an ever-present feature of mountainous regions worldwide and provide direct evidence of the temporal and spatial record of sediment flux to drainage basins and sedimentation in adjoining basins over geological timescales (e.g. Whipple & Traylor, 1996; Jones, 2004). Recent research has considered how climatic and tectonic processes influence alluvial fan sedimentation, processes operating on alluvial fans and how fans respond to these changes (e.g. Harvey et al., 2005; Quigley et al., 2007). Tectonism is frequently held responsible for abrupt coarsening and cyclical sedimentation within alluvial fan successions. Whilst it is accepted that tectonism provides the opportunity for alluvial fan development through the creation of topography, increasing gradients of river systems supplying sediments, and the creation of accommodation for the storage of sediment flux, the influence of climate is often neglected (Frostick & Reid, 1989; Allen & Densmore, 2000; Densmore et al., 2007). The role of precipitation is essential for the deposition of sediment onto the fan and increasingly climate is being regarded as a significant controlling factor on fan development (e.g. Harvey et al., 2005; Pope & Wilkinson, 2005; Weissman et al., 2005; Quigley et al., 2007). However, it has been recognised that further complications arise from continual complex coupled geomorphological responses (Humphrey & Heller, 1995) further complicating the allocation of alluvial fan sequences to tectonic and/or climatic events. Additional studies of alluvial fans are required to provide further insights into the interplay between tectonics, climate change and the depositional processes operating on alluvial fans and to assess how landscapes may respond to future climatic and tectonic changes. If climate were the dominant mechanism for fan development, it would be expected that a strong climatic or orbital signal would be recorded in the depositional patterns within the fan succession. These would overprint any tectonic patterns. The critical discriminators for determining the dominant mechanism in controlling the development of the alluvial fans would be to take into account the regularity and timescales of the depositional packages within the fan succession. Tectonic processes occur irregularly over large timescales and would not be correlatable to the regular patterns that would be typical of climatic Milankovitch scale cycles.

This study focuses on elucidating the palaeoflood hydrology of alluvial fans deposited adjacent to the Troodos Massif in southern Cyprus (Fig. 4.1). The Neogene to

Recent sedimentary succession of southern Cyprus records uplift and extension of the Cyprus supra-subduction zone in response to northerly subduction. Tectonism has therefore previously been considered a dominant controlling factor in sedimentation (e.g. Poole & Robertson, 2000) and is still responsible for frequent large earthquakes (Mb 6>; Papadimitriou & Karakostas, 2006). Our results indicate that although the fans are located within one of Europe's most tectonically active areas, tectonism only exerted the control on the positioning of the alluvial fans. The switches in Pleistocene climate, from wet to dry modes and the resultant changes in palaeoflood hydrology, were the primary driver of alluvial fan sedimentation.

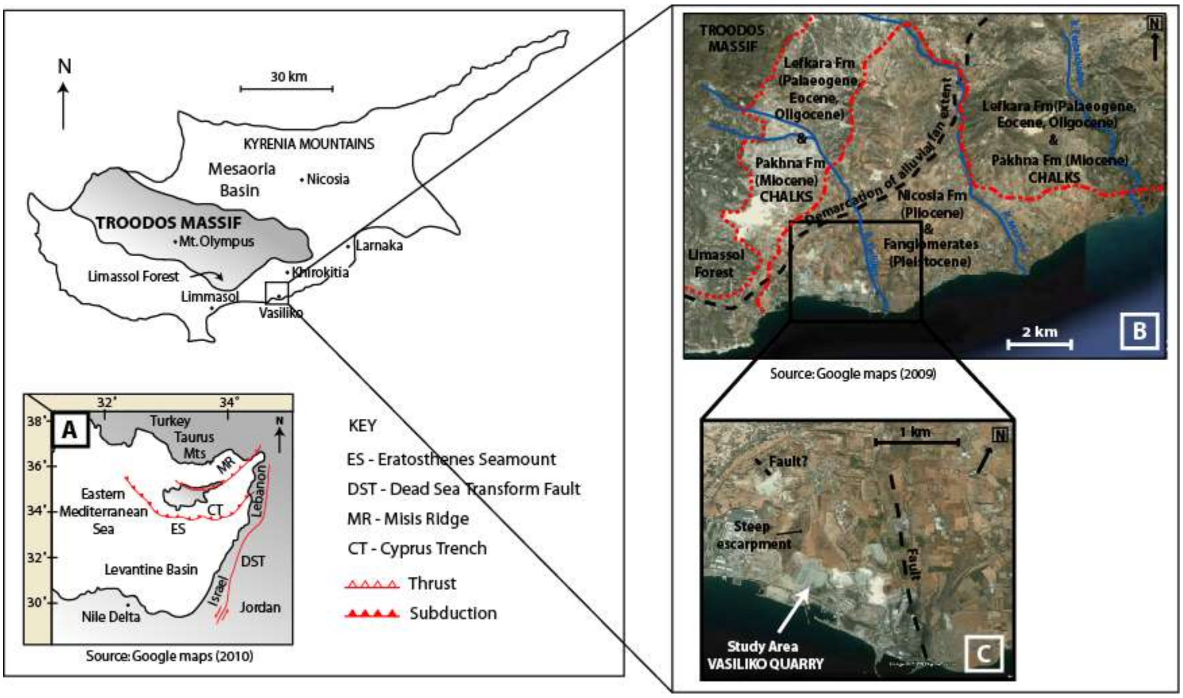


Figure 4.1 – (A) Location of Cyprus with respect to the Cyprus supra-subduction zone, (B) basic geology of the Vasiliko area and (C) location plus structural setting of the Vasiliko Quarry fans.

4.2 Geological setting

4.2.1. General setting

The island of Cyprus lies in the Levantine Basin, to the north of the active Cyprus supra-subduction zone; the present day boundary between the converging African and Eurasian plates (Fig. 4.1). The Troodos Massif, located on the hanging wall of the Cyprus subduction zone, is composed of an oceanic crustal sequence, the highest point of which is denoted by Mount Olympus (1951 m a.p.s.l.). Uplift of the Troodos Massif is thought to have occurred in stages, with gradual uplift occurring from the late-Cretaceous to late-Oligocene followed by a more rapid phase during the Miocene in association with the initiation of the northwards dipping subduction zone (Orszag-Sperber et al., 1989; Poole & Robertson, 1991; Robertson et al., 1991; Eaton & Robertson, 1993; Stow et al., 1995; Schirmer, 2000; Davies, 2001). Uplift and extension continues from the Neogene to the present day (Robertson, 1977; Poole et al., 1990; McCallum & Robertson, 1995). During the Plio–Pleistocene a general pattern of regression is recorded in the supra- subduction zone sedimentary succession of marine silts (*G. inflata* Biozone, based on the presence of the eponymous zonal species in Iaccarino, 1989) through to fan delta deposits culminating in alluvial fans (Fig. 4.2).

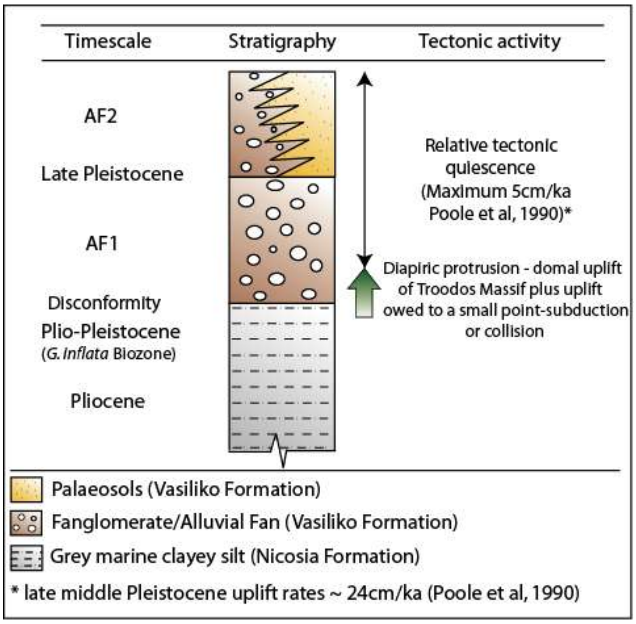


Figure 4.2 – Geological succession, chronostratigraphy and general geological history of the Vasiliko area

Onset of Troodos Massif uplift during the latest Miocene in association with the initiation of the northwards dipping subduction zone and approximately 2 km of uplift since the latest Pliocene to earliest Pleistocene (Eaton & Robertson, 1993; Stow et al., 1995; Schirmer, 2000; Davies, 2001), provided the relief and source necessary for fan building. A record of raised beaches at heights 100-110 m, 50-60 m, 8-11 m and <3 m suggests that uplift of the region was episodic (Poole et al., 1990; McCallum & Robertson, 1995) and indicates tectonically or climatically induced eustacy. An uplift rate between 130 and 185 ka, just prior to the deposition of the late Pleistocene alluvial fan succession described in this paper, has been estimated at ~24 cm/ka (Poole et al., 1990), with a notable reduction to ~5 cm/ka from 116 ka to the present day (Poole et al., 1990). This indicates a 'relative' tectonic quiescence during deposition of the Vasiliko fans. Comparative work on the Dead Sea alluvial fans, Israel (Frostick & Reid, 1989; Trune et al., 1998) has shown that in this type of extensional regime, regional patterns of faulting and subsidence control distribution and overall fan morphology.

4.2.2. Review of the alluvial fans in southern Cyprus

The alluvial fans in Cyprus (their sediments often termed 'fanglomerates') are thinly scattered across the island (refer to Poole & Robertson, 1998 for fan distribution). The fans in the north (Mesaoria Plain) are better developed and more extensive than those in the south. The alluvial fans under consideration are not exposed any further north than the A1 motorway (refer to Fig. 4.1). The fans exhibit a terraced morphology as has been identified by numerous researchers (Bagnall, 1960; Gomez, 1987; McCallum, 1989; Poole & Robertson, 1998), with four main terraces documented. The descriptive terminology for these terrace/fanglomerate phases F1 (oldest) to F4 (youngest) was developed by Poole & Robertson (1998), each successive terrace has been formed at a topographically lower altitude. The lowermost fanglomerates in southern Cyprus correlate with littoral marine terraces formed at <3 m and 8-11 m, these have been dated as 116–130 ka and 185–192 ka respectively (Poole et al., 1990) and provide a maximum age for the Vasiliko fan complex. These have been interpreted as being eustatically controlled (Poole & Robertson, 1998).

Poole & Robertson (1998) suggested the alluvial fan deposits at Vasiliko were early to middle Pleistocene (F1 or F2) in age, based primarily on clast content. Field relationships, U/Th dating of calcrete nodules within the fan complex and correlations with the palaeosol stratigraphy in the wider eastern Mediterranean are used to assign a late Pleistocene age (see Section 4.2.4 overleaf).

4.2.3 Vasiliko alluvial fans

The study area is focused on a major alluvial fan complex, in the area of Vasiliko, located approximately 20 km from Limassol and 30 km from Larnaka, southern Cyprus (Fig. 4.1). The catchments encompass an area of ~12.5 km^2 (not including any fan material that may have been bypassed into the sea) and locally exhibit a few 100 m's of relief between the summit surfaces and present day valley floors that pass down to sea level. The morphology of the catchments is governed by the Troodos Massif, the sheeted dykes and basaltic composition (pillow basalts) of the underlying bedrock. Further downstream Cenozoic carbonates and siliciclastics are incised into by the fluvial systems with numerous terraces. All of the lithologies from the catchment area are represented in the alluvial fans.

The Vasiliko fans are the best-developed fans in southern Cyprus and cover an area of ~1.5 km^2. The fans comprise several lobes of sedimentation with two dominant alluvial fan phases that coalesce westwards through time. Source catchments at elevations of ~600 m.a.s.l, have developed well-defined fan geometries and the fans are truncated downstream by present day sea level.

4.2.4 Age constraints on the Vasiliko alluvial fans

The maximum age range of the Vasiliko Quarry alluvial fan succession is constrained by the Cyprus-wide dated horizon of the *G. inflata* biozone (Pliocene to early Pleistocene; 1.8–2.1 ma) based on planktonic foraminifera from the underlying marine clayey silts (Nicosia Formation; Fig. 4.2).

In a number of localities around Cyprus (e.g. Pissouri coastal section, Khirokitia, Episkopeio-Arediou) grey clayey silts yielding *G. inflata* biozone foraminifera (Chapter 2) are overlain by marine fan delta or debrite sediments, which are subsequently overlain by alluvial fan deposits. The fan delta succession in southern Cyprus is now known to be early Pleistocene in age (Kinnaird, 2008) and appears to be part of an early to middle Pleistocene depositional system (Chapter 3). New U/Th dates for calcrete nodules within the first palaeosol overlying the oldest alluvial fan lobe - AF1 (see below) at Vasiliko and a calcrete horizon overlying alluvial fans in Pissouri provide 59 ka and 52 ka ages respectively (Waters et al., unpublished data). This age assignment maps into the precessionally paced palaeosol stratigraphy for the Negev desert, Israel (Goodfriend & Magaritz, 1988; Gvirtzman & Wieder, 2001). In addition to this the lowermost dated raised beaches that are coincident with the youngest phases of alluvial fan deposition (F3 and F4 - previously described in Section 4.2.2) must also provide a maximum age constraint on the fans. It is therefore concluded that the alluvial fan complex at Vasiliko lies disconformably on late Pliocene to early Pleistocene grey clayey silts and spans the last ~120 ka and is consequently late Pleistocene to Holocene in age (MIS 5e to MIS 1).

4.3 Methodology

A detailed sedimentological study has been carried out on the alluvial fan sections exhibited in the Vasiliko Quarry of southern Cyprus (Figs. 4.1 & 4.2). The fans are well exposed due to active quarrying; this provides excellent three-dimensional exposures cutting across the core of the fan complex. The facies and associated sedimentary structures are easily documented in the working faces of the quarry. Thirteen graphic logs were measured at a centimetre scale around the quarry with particular emphasis on collection of maximum clast size (the measurement of a minimum of twenty of the largest clasts in the vicinity of the point of measurement), degree of sorting, sedimentary structures and determination of palaeocurrent directions from predominant clast imbrication, pebble clusters and low angle planar cross-bedding.

Photomosaics of each quarry face were constructed to aid the architectural analysis. The use of bounding surfaces has been applied to determine the relative timescales of deposition that are involved, which are used to differentiate between autocyclic and allocyclic processes (Miall, 1996). Width–thickness (W/T) measurements were taken of all the channel bodies, point bars and open framework gravels (OFG). W/T allows for detailed analysis of channel geometries, water depth within the channels, palaeoflood hydrology and a better understanding of the fluvial processes operating on the fan surface.

4.4 Sedimentology of the alluvial fans

The Vasiliko Quarry alluvial fan sequence disconformably overlies marine grey clayey silts of the Nicosia Formation (Fig. 4.2) and comprises two lobes (AF1 and AF2). Figure 4.2 shows the general stratigraphy of the area and Figure 4.3 demonstrates the overall architecture displayed by the alluvial fan facies within the Vasiliko quarry (faces A to H). The quality of the exposures enables both lateral and vertical variations in the fan sequence to be determined.

In general AF1 comprises two large-scale conglomeratic channels (LCC), separated by sandy braided fluvial deposits (SBF). AF2 is predominantly conglomeratic, dominated by stacked point bars and open framework gravels. The top of AF1 is marked by 5/6 palaeosol horizons that interfinger with AF2.

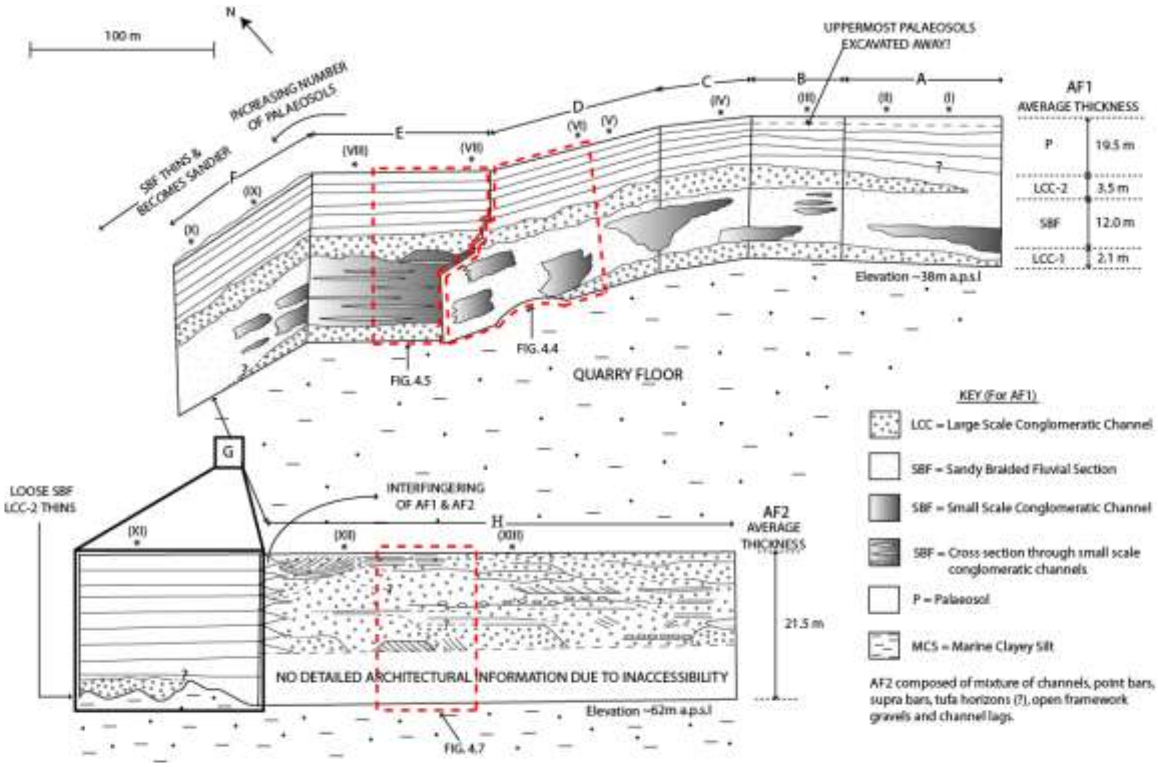


Figure 4.3 – Schematic 3D diagram representing the main quarry faces of the Vasiliko Fan System – roman numerals in parentheses indicate log localities, logs are depicted in Fig. 4.6.

4.4.1. Alluvial Fan 1 (AF1)

The two LCC consist of clast- to matrix-supported conglomerates that are moderately to poorly sorted with predominantly subrounded to subangular large pebble sized clasts. The clasts are derived from the Troodos Massif and are composed of a mixture of pillow basalts, diabase dykes, gabbro and plagiogranite, with a smaller percentage represented by Cenozoic sedimentary clasts composed of chalk and limestones from the marine phases of the fringing sedimentary basins (Fig. 4.1). Outsize clasts (maximum size of 79 cm) are abundant throughout, often being concentrated towards the top of the channels, where a coarsening upwards trend can be noted. Pebble clusters are plentiful within the channels as are crudely defined foresets (Figs. 4.4 & 4.5). These foresets often exhibit a cyclical abrupt coarse-fine texture as can be seen in Table 4.1a.

Palaeoflow directions determined from imbricated clasts and pebble clusters indicate a consistent south to southeasterly palaeoflow direction in agreement with Poole & Robertson (1998). Rare features within the channels, with particular reference to channel two include <1 m thick wedge-shaped features composed of pebbly horizontally stratified beds with limited lateral extent (Table 4.1b) and partially developed open framework gravel (OFG) textures usually developed in the uppermost part of the channel. In addition to these features intermittent sand layers present throughout the channel bodies are common. Both channels exhibit erosive, sharp basal contacts.

The SBF between the two conglomeratic channels is predominantly composed of sand with small-scale conglomeratic channels scattered throughout (Figs. 4.4 to 4.6). The sand grain size is very variable and laterally inconsistent. There are three main types of sand that characterise this facies, all of which are described in Table 4.1 c, d and e. Throughout the sandy parts of this facies are occasional freshwater Planorbis gastropods and plentiful small-scale gravel stringers (up to 44 cm thick and 7 m wide). Calcrete horizons aligned parallel to the bedding are common (Table 4.1f), with the prominent more laterally continuous horizons appearing to thin up section towards the uppermost LCC. The moderately to well sorted braided conglomeratic channels lying within this section display migration of channels at the base of the facies and stacked channels towards the top of the succession (Fig. 4.4); these are described in Table 4.1g. A number of these braided channels display foresets depicted by abrupt coarse-fine cyclical intercalations, as seen in the LCC, whilst in other areas foresets in the succession appear to alternate flow direction frequently up section (Fig. 4.5).

Numerous intercalations of Terra Rossa and calcrete horizons directly overlay AF1 (Fig. 4.6). The Terra Rossa horizons depicted by a brown/red colouration are often identified by the presence of vertical branching rhizoconcretions (reaching up to 20 cm in length). Both types of the palaeosols exhibit rounded to subrounded gravel/pebble matrix supported stringers a single clast thick up to ~5 cm thick. These stringers are often focussed at the base of the palaeosol horizons and display a lenticular geometry. Contact with the fan is very sharp and planar as are the subsequent contacts between the palaeosols.

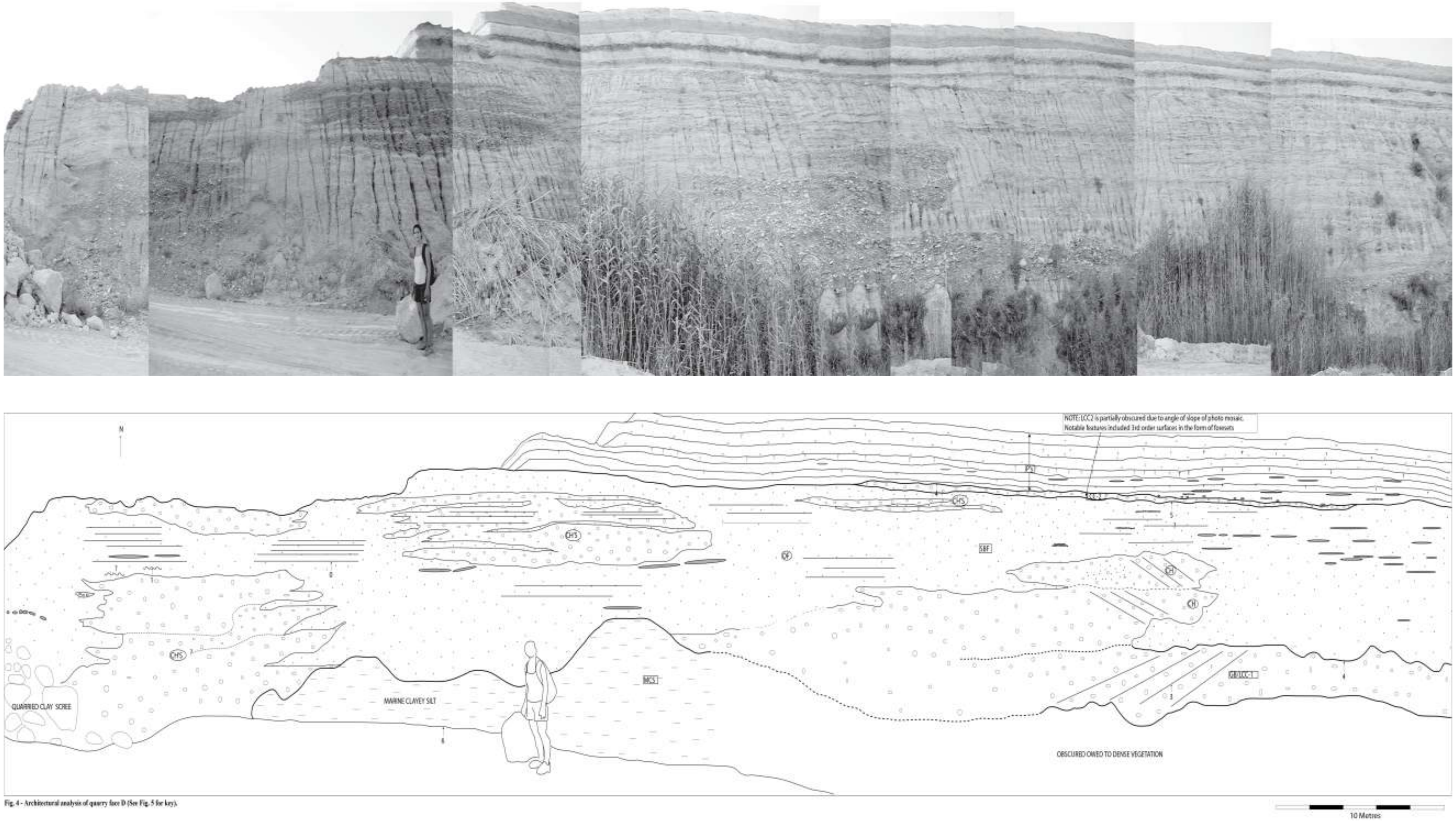


Figure 4.4 – Architectural analysis of quarry face D. (see Fig. 4.5 for key)

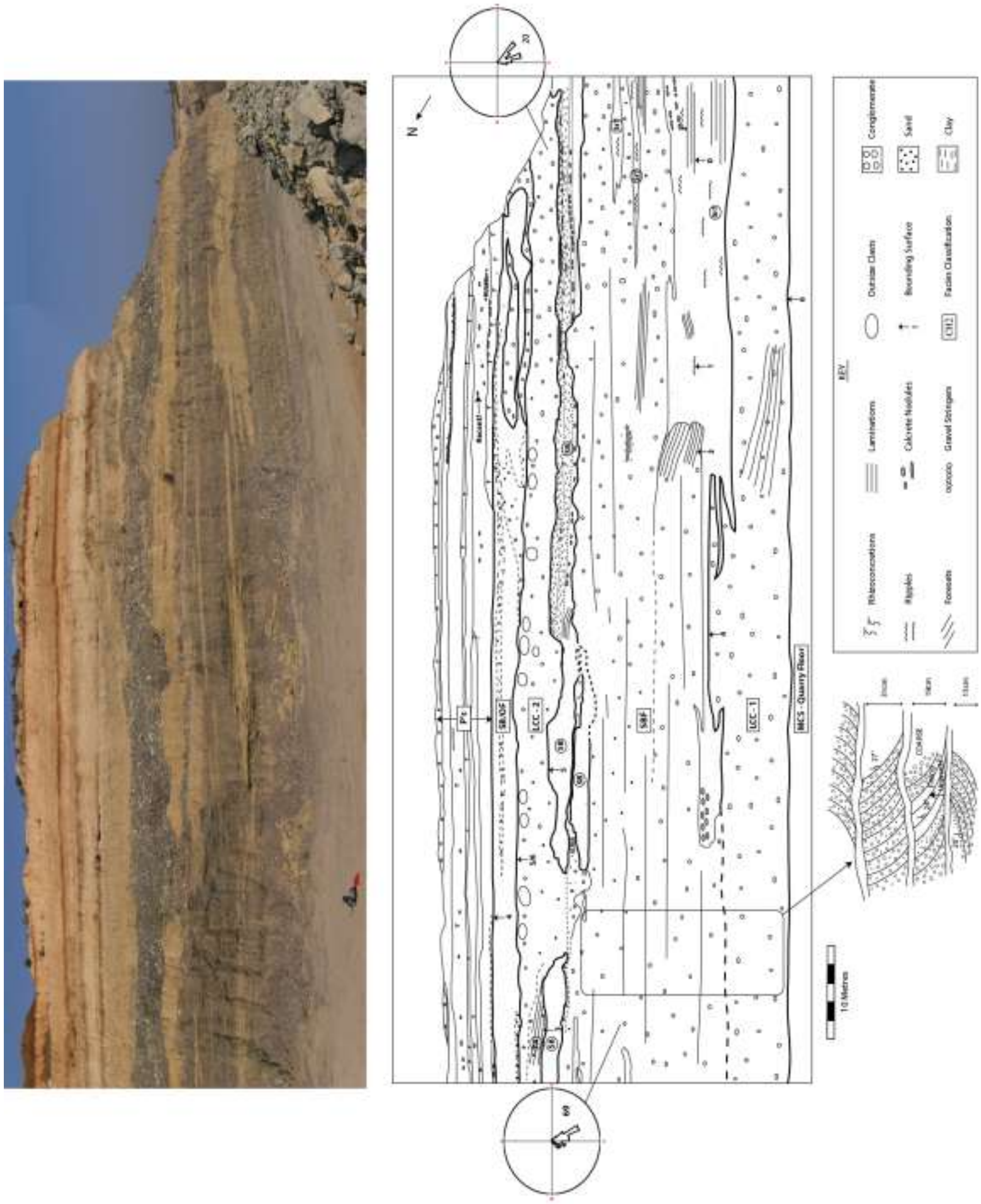


Figure 4.5 – Architectural analysis of quarry face E

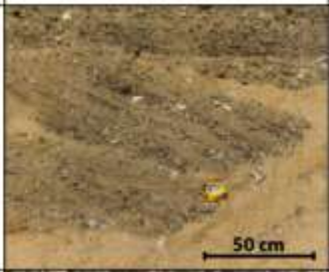
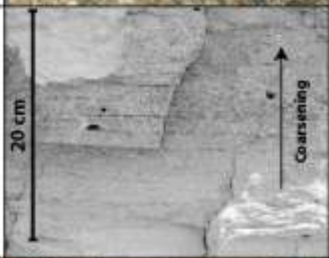
DESCRIPTION	PHOTOGRAPH OF FEATURE	LOCATION OF FEATURE IN QUARRY	INTERPRETATION
a Foresets either in lateral accretion, downstream accretion, x-bedding Abrupt distinction of foresets between coarse layers and fine layers		Quarry Face A Quarry Face D Quarry Face E	Perennial environment subject to fluctuating flow conditions Coarser grained foresets represent periods of increased rainfall within the depositional system (Frostick & Reid, 1989)
b Rare features within the LCC2 Pebbly/granular stratified wedge shaped horizons with sandy matrices Characterised by fine to medium sand, often with a striated appearance		Quarry Face D	Likely to signify depositional events at the end of a discharge cycle when flow velocities have waned Stratification likely to be owed to upper flow regime plane bed conditions (Allen, 1981)
c Intercalations of v.fine to fine sand, mudstone & clayey siltstone 'Varve' like appearance Slightly rippled Occasional remnants of organic matter Slight orange tinge		Quarry Face D & E : Abundant throughout Braided fluvial facies	Periods of protracted settling from suspension during lower flow regimes in the form of waning flood deposits. Standing body of water - overbank deposition
d Cross bedded sands Coarsens upwards from Fine-Medium/medium sand, moderately sorted, sub-angular - subrounded to Medium-coarse sand, poorly sorted, subangular - subrounded		Quarry Face E : Abundant throughout Braided fluvial facies	Bar feature within the system Infilling of flat bottomed scours?
e Well laminated sands Coarsening upwards Fine - medium sand Subangular - subrounded		Quarry Face A & E : Abundant throughout Braided fluvial facies	Upper flow regime conditions Episodic flood within the system
f Well cemented calcrete horizons parallel to bedding Some calcrete horizons depicted by nodules in laterally disconti-nouous horizons Quite regularly spaced Thinning of horizons towards LCC2		Quarry Face A,B,C,D,E : Well cemented layers abundant throughout Braided fluvial facies Quarry Face F: Infrequent & discontinuous throughout Braided Fluvial facies Quarry Face A,B,C,D,E,F,G: Discontinuous layers in palaeosol horizons	Calcrete nodules and horizons indicative of semi-arid environment & strongly seasonal precipitation regime (Wright & Tucker, 1991; Candy et al., 2006) Precipitation of calcrete near or below the watertable (Mack & Leeder, 1999) Thinning upwards of horizons may suggest an environment subject to increasingly wetter conditions

Table 4.1 – Sedimentary features within the Vasiliko Quarry Fan System

DESCRIPTION	PHOTOGRAPH OF FEATURE	LOCATION OF FEATURE IN QUARRY	INTERPRETATION
g Migratory channels Each successive channel is finer than the previous one, apart from the uppermost channel Predominantly clast supported & moderately sorted		Quarry Face D	Migration of channels suggests infilling of accommodation space, instead of incising the channels were forced to switch laterally
h Well laminated granular sandy horizons, sand is medium grained Mostly noted overlying bar features Some of sand bodies contain nodular calcrete, particularly those higher up section		Quarry Face A Quarry Face H	Suprabars Upper flow regime conditions but during the waning stage of floods
i Open framework gravel Little to no matrix Clast Supported Often depicted by preferentially eroded out horizons Subrounded to rounded clasts		Throughout the lobe: Quarry Face H Infrequent & thin layers, partially developed texture: Quarry Face C Quarry Face E Quarry Face F	Often found in a perennial environment (Jones & Frostick, 2008) Feature of flood recession - a falling stage phenomenon (Allan & Frostick, 1999)

Table 4.1 continued – Sedimentary features within the Vasiliko Quarry Fan System

4.4.2. Alluvial Fan 2 (AF2)

This sand-poor alluvial fan lobe displays a complex depositional history in the form of numerous conglomeratic bodies, channels, occasional sandy beds and open framework gravels (OFG). The gravel bars tend to thin to the south, are predominantly poorly sorted, matrix supported but often with clast supported areas containing pebble size subangular to subrounded clasts. A south to southeasterly palaeoflow is determined from imbrication and low angle planar cross-bedding. Many of these bars coarsen upwards and display clear foresets particularly at the downstream end of the feature. The sand bodies, which tend to overlie the bars, described in Table 4.1h, tend to become more abundant and thicken in a southerly direction. The OFG horizons (Table 4.1i) are associated with bars and channel fills throughout the succession and depicted by medium to large pebble sized clasts with little to no matrix (Fig. 4.6).

4.5 Interpretation

4.5.1. Alluvial Fan 1

The two LCC are poorly sorted, occasionally matrix supported and chaotic in nature, and are commonly interpreted as debris flows. However the presence of numerous streamflow characteristics such as pebble clusters and imbrication of clasts creating armouring of the channel (Laronne & Reid, 1993; Reid et al., 1992; Jones et al., 1999; Jones & Frostick, 2008), open framework gravels (OFG) (Steel & Thompson, 1983; Allan & Frostick, 1999), intermittent well organised layers and crudely horizontally stratified clast supported conglomerates (Ridgway & Decelles, 1993), indicates that deposition was by streamflow processes with a strong perennial component. The presence of normally graded foresets within the channels also supports our interpretation. Many of the individual sets within the LCC alternate between sharply defined fine and coarse layers. Smith (1990) documented similar rhythmic features in Budleigh Salterton Pebble Beds of southwest England and noted their common occurrence in gravel bed streams. The size of the sets suggests considerable channel-bar relief with water depths of at least 2 m (Smith, 1990). A number of longitudinal bars are evident in both channels and are indicative of relatively high flood and sediment discharges (Hein & Walker, 1977; Mack & Leeder, 1999; Collinson et al., 2006). Furthermore, the presence of large pebble to large cobble sized clasts in the basal scours of the channels, particularly in the uppermost LCC is indicative of a rapid periodic and possibly flashy mode of emplacement (Jones et al., 2001). It is thus concluded that the two LCC within AF1 represent relatively high magnitude stream flood deposits similar to those described in the Sanghori system, southeastern Korea (Jo et al., 1997).

The occurrence of slight rippling of fine-grained sandstones, siltstones and mudstones with a varve-like morphology in the SBF section is interpreted to represent periods of protracted settling from suspension during lower flow regimes in the form of waning flood deposits (Steel & Thompson, 1983; Frostick & Reid, 1989). A standing body of freshwater was present as indicated by the occurrence of abundant Planorbis gastropods. It is thus concluded this is an overbank depositional setting (Ridgway & DeCelles, 1993).

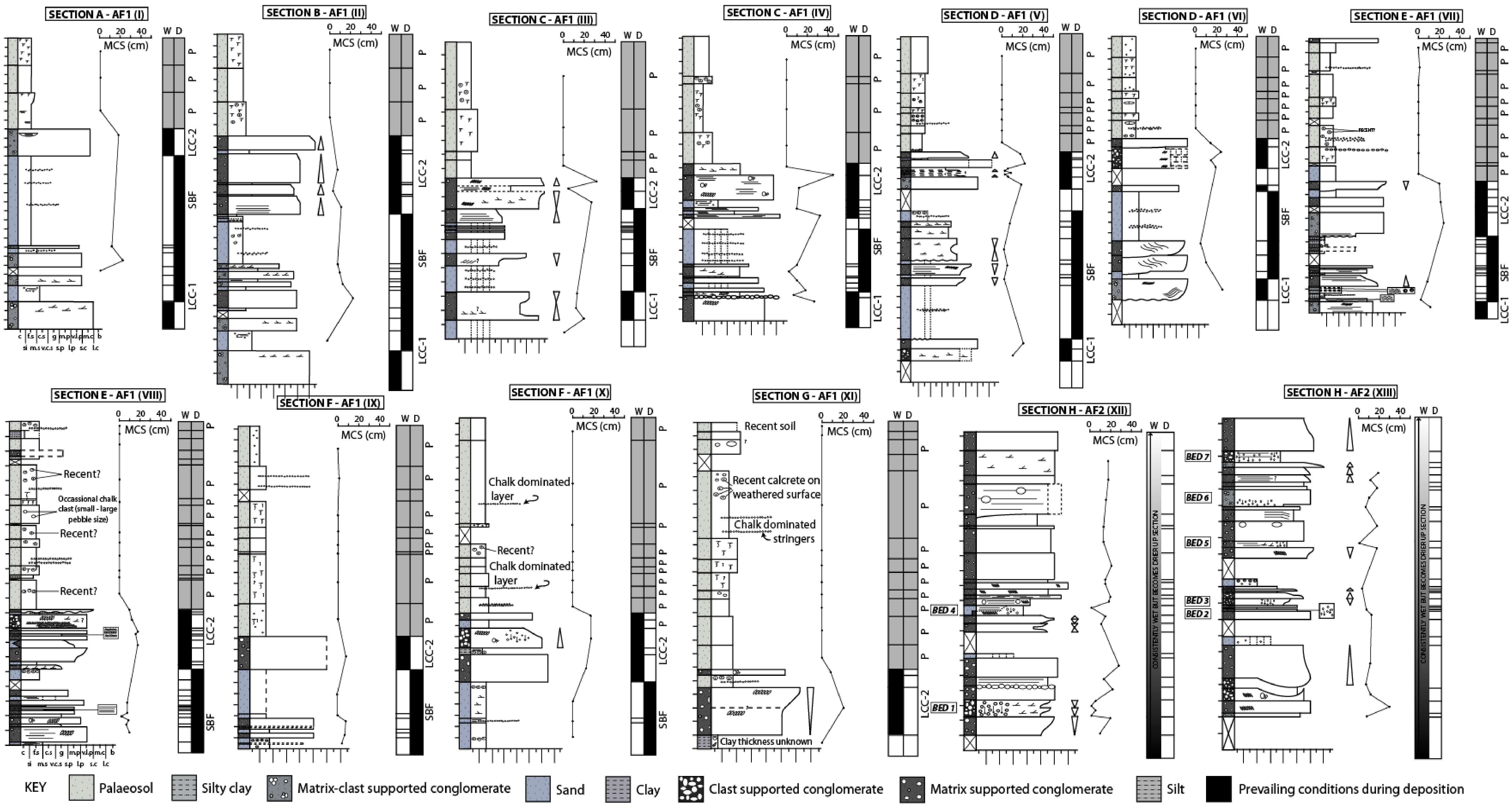


Figure 4.6 – Detailed logs of the Vasiliko Quarry Fan System. Note: AF2 logs Beds 1-7 relate to Figure 4.7 and palaeosols cannot be definitively assigned as wet or dry due to seasonality effects (explained in section 4.5.1). P = palaeosol, SBF = sandy braided fluvial, LCC = large scale conglomeratic channel, MCS = maximum clast size, W/D = wet/dry, logs are partioned in 1m intervals

The conglomeratic, braided channels distributed throughout this facies exhibit many of the features as described for the two LCC. The channels also contain a diverse array of lower flow regime sedimentary structures and a multitude of transverse bars within the channels suggesting relatively low flood and sediment discharges (Hein & Walker, 1977; Collinson et al., 2006), all of which indicate a perennial flow regime. Furthermore, the channels are isolated at the base of the succession and have a stacked morphology in the uppermost parts. This suggests that accommodation was limited and the perennial braided streams were continuously filling up the accommodation available before they became fixed in position and/or more accommodation became available. Within some of the channels there is evidence of downstream accretionary foresets displaying the abrupt coarse-fine cyclicity. The presence of small-scale foresets (maximum 31 cm thick) alternating regularly in opposite avalanching directions (Fig. 4.5) suggests fluctuating flow conditions and regular variability in discharge rates. Flow velocities calculated for the channels identify that subcritical flow was the norm with values of Froude (Fr) 0.0006-0.1 (Table 4.2). The lithofacies heterogeneity as depicted by the frequent minor bounding surfaces (i.e. 2nd and 3rd order) suggests a system experiencing seasonal/long term variability in the flow discharge and is in agreement with the above interpretations (Jones et al., 2001).

The development of calcrete and Terra Rossa palaeosol horizons identifies localised fan and tectonic stability (Retallack, 1997; Widdowson, 1997; Wang, 2003) at a time when minimal sediment was being deposited and a dominance of pedogenesis (Mack & Leeder, 1999). The occurrence of pedogenic calcrete nodules suggests a semi-arid environment during either a regime in which the region was receiving very small amounts of annual precipitation or precipitation was relatively high but seasonal. In the Mediterranean at the present day cool wet winters and warm dry summers (with summer months receiving three times less precipitation than winter months) are ideal for pedogenic calcrete formation (Candy et al., 2006). The occurrence of branching rhizoconcretions within some of the palaeosols would imply a scarcity of water and hence a semi-arid environment, which concurs with the presence of the calcrete nodules. Terra Rossa development typically occurs within the same climatic setting as calcretes where regions can experience periods of high rainfall but with dry seasons and warm temperatures (Retallack, 2001).

Location of channel	h (m) (maximum)	S	$\bar{U}$ (m/s)	D_{50} (mm)	D_{90} (mm)	Specific stream power (W m^{-2})	Froude no.
LCC-1 (average)	2.1	0.003	0.32	65.3	184	191	0.07
LCC-2 (average)	3.5	0.002	0.32	69.5	209	209	0.05
SBF channels	1.5	0.005	0.01	8.0	12.0	0.74	0.003
SBF channels	1.0	0.015	0.155	16.0	24.0	22.8	0.05
SBF channels	0.75	0.015	0.01*	12.0	N/D	1.10	0.004
SBF channels	0.30	0.019	0.001*	6.0	N/D	0.06	0.0006
SBF channels	1.0	0.011	0.01*	12.0	N/D	1.09	0.003
SBF channels	0.47	0.003	0.20	15.0	37.5	2.77	0.09
SBF channels	0.28	0.004	0.175	12.5	35.0	1.92	0.11
SBF channels	1.0	0.001	0.01*	12.0	N/D	0.10	0.003
SBF channels	0.6	0.002	0.01*	12.0	N/D	0.12	0.004
SBF channels	0.25	0.003	0.25	8.0	64.0	1.84	0.16
SBF channels	0.3	0.004	0.01*	12.0	N/D	0.12	0.006
SBF channels	0.75	0.011	0.32	87.5	155	129.5	0.12

Table 4.2 – Stream power and Froude number values for channels within AF1 of the Vasiliko Quarry Fan System. Note: * Based on D_{50} values. Refer to Appendix H for formulations

4.5.2. Alluvial Fan 2

This phase of the alluvial fan development can be classified as a mixed braided fluvial and meandering river succession dominated by stacked point bars, numerous OFG horizons, a number of channel fills and variable slope and stream power values (Table 4.3). Simulation experiments have shown that discrete sections of beds break-up and dilute prior to commencing transportation, almost instantaneously (Allan & Frostick, 1999; Brasington et al., 2000; Frostick et al., 2008). This process is controlled by the fluid flow above the bed and below the bed surface, and the particle interactions causing the bed to behave as a large aggregate and not as individual grains. During entrainment in mixed bedload rivers, fine-grained material can move down into subsurface pores, creating a reservoir of fine sediment. Thus alternating layers of matrix-filled and OFG can be created (Frostick & Jones, 2002; Frostick et al., 2008). The presence of OFG occurs from the process of winnowing of sediment once the gravel is in place and stabilized; this occurs mostly during flood recession (Allan & Frostick, 1999), a falling stage phenomenon and often found in a perennial environment (Jones & Frostick, 2008).

The recognition and use of the OFG textures (Beds 1 to 7, Figs. 4.6 & 4.7) for determining a palaeoflood hydrology of the alluvial fan is one of the first palaeohydraulic reconstructions using such a texture. Maximum clast size (D_{90}) within the OFG, palaeochannel depth and matrix size all provide a palaeoshear velocity, combined with the use of the Harms et al. (1975) Curve (Table 4.3). The assessment of the measurements of the relative components described above and the input factors for the calculations i.e. maximum clast size, depth of channel are explained in Appendix H. Calculation of Fr from these results gave subcritical flow values all significantly <1 (Table 4.3). Together these observations suggest that the dominant process on the alluvial fan was perennial flow with a lesser component of flashiness to the flood events, but still channelised (Fig. 4.7).

4.5.3. Depositional model

The two LCC of AF1 record a wetter environment whilst the SBF regime is indicative of drier conditions experiencing seasonal variability (Fig. 4.8a, b, c). The sufficiently deep (up to 3.5 m), large scale nature of the LCC with relatively well organised bedforms represents relatively high and steady discharges that would be expected of a

Location of OFG within AF2	D_{50} (mm)	D_{50} (mm)	Minor matrix size (mm)	Palaeo shear velocity (m/s)		Palaeo channel depth (m)	Palaeoslope	Froude no.	Specific stream power (W m^{-2})
				Rolling	Suspended				
BED 1	40	80	0.19-0.25	0.27	0.005	2.0	0.0019	0.06	10.1
BED 2	2	30	0.25-0.50	0.17	0.005-0.011	2.4	0.0001	0.04	0.4
BED 3	24	-	0.25-0.50	0.31	0.005-0.011	0.2	0.0113	0.22	6.9
BED 4	8	110	0.25-0.50	0.31	0.005-0.011	1.0	0.0008	0.10	2.4
BED 5	8	41	0.25-0.50 to 0.5-1.0	0.20	0.011-0.160	1.0	0.0008	0.06	1.6
BED 6	96	112	0.25-0.50	0.32	0.005-0.011	2.0	0.0045	0.07	28.3
BED 7	4	6	-	0.005	-	1.5	0.0003	0.001	0.02

Table 4.3 – Palaeoflow velocity calculations from the open framework gravel horizons in AF2 of the Vasiliko Quarry Fan System

wetter environment (Ridgway & DeCelles, 1993; Jones et al., 2001). Abruptly alternating fine-coarse foresets identified within many of the conglomeratic channels are likely to represent fluctuating flow conditions (Steel & Thompson, 1983). The coarser layers potentially indicating periods of increased rainfall and subsequent increased flow velocities, a feature which has been noted in the Dead Sea Rift fans in Israel (Frostick & Reid, 1989). Sediment supply and rate of catchment erosion are related to stream power, which is generally attributed to precipitation intensity (Jones, 2002; Suresh et al., 2007), in addition it is well known that sediment yields tend to increase with increasingly effective precipitation through the arid to semi-arid transition (Langbein & Schumm, 1958). The lowered sediment yield within the SBF as compared to the overlying and underlying LCC indicates that the climatic regime became more arid (Nemec & Postma, 1993); this is further substantiated by the calculated stream power values (Table 4.2), whereby the SBF section exhibits much lower values as compared to the LCC. This change in climatic conditions is particularly well demonstrated between the SBF and uppermost LCC, where calcrete horizons within the SBF appear to thin up section towards the uppermost LCC. This upward thinning may represent less carbonate being precipitated and that a wetter environment was starting to prevail. AF2, which is contemporaneous with deposition of the palaeosols, demonstrates a consistently wet environment (with minor fluctuations) as demonstrated by palaeohydraulic analysis, with a potential move to a significantly drier climate within the uppermost portion of the deposit (Figs. 4.7 & 4.8d).

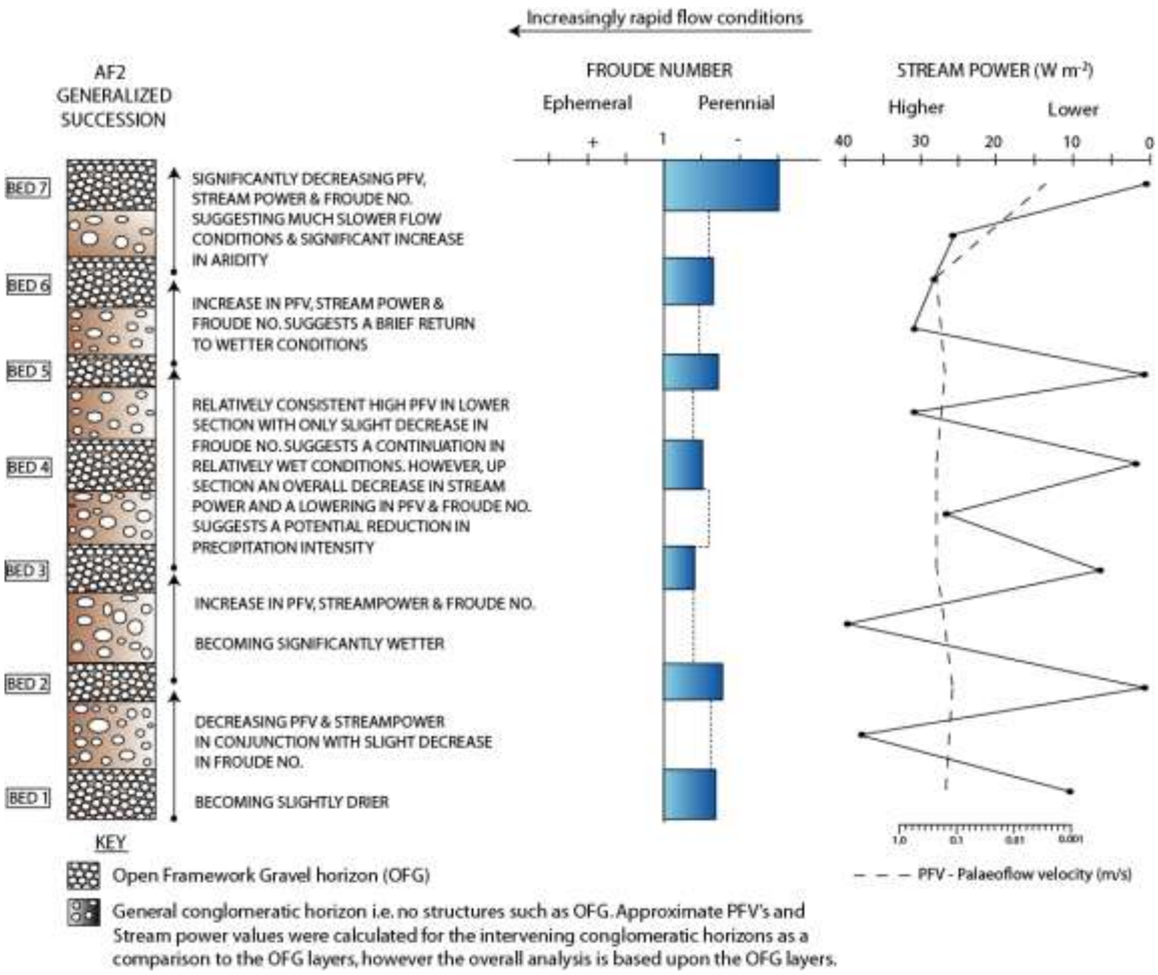


Figure 4.7 – Palaeoflow conditions in AF2 as deduced from Open Framework Gravel Horizons - Vasiliko Quarry Fan System

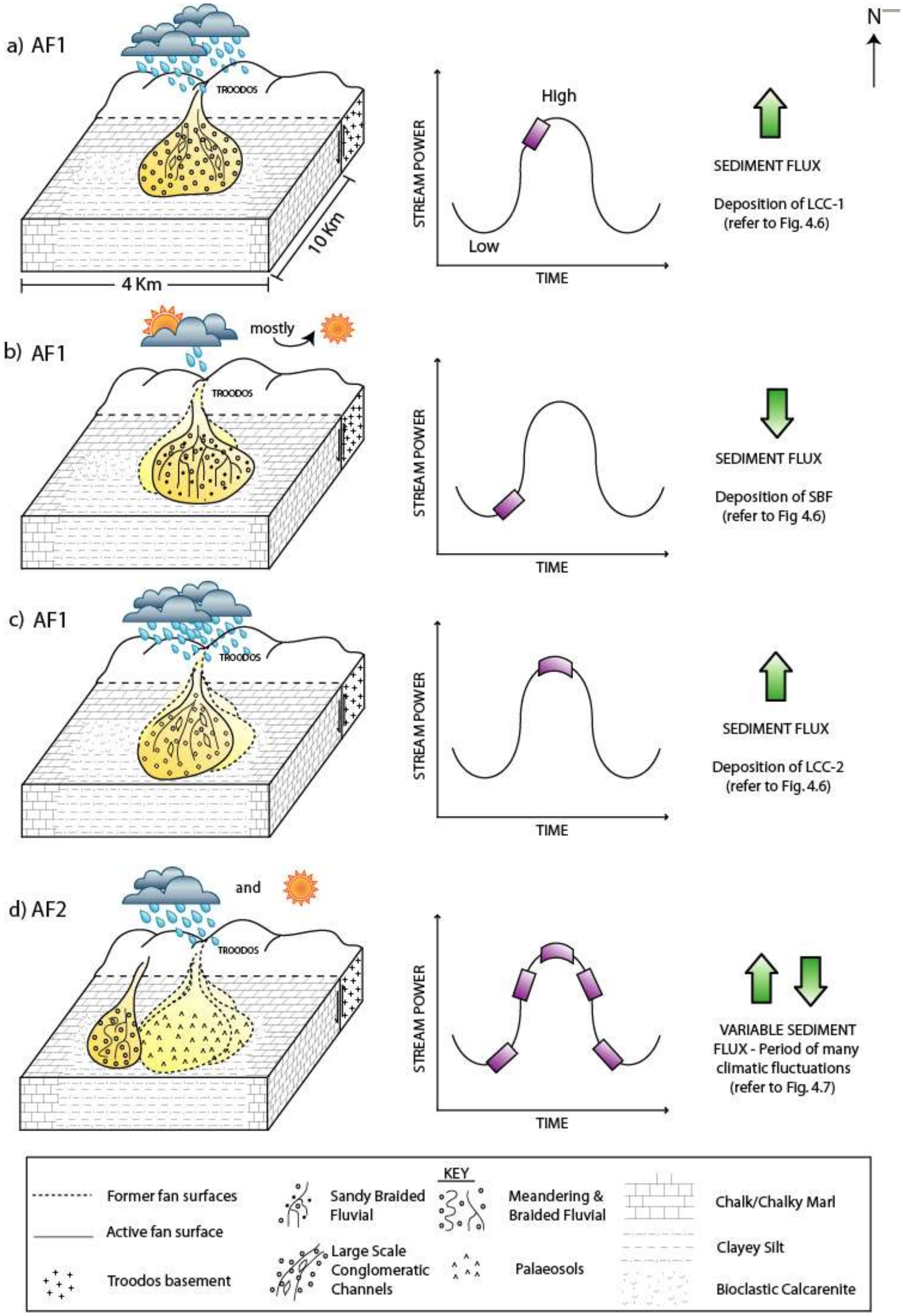


Figure 4.8 – Schematic block diagrams representing the Vasiliko Fan System and lobe switching throughout the development of AF1 (a to c) with subsequent abandonment of AF1 and renewed fan sedimentation in AF2 (d)

4.6 Discussion

The Vasiliko alluvial fans of southern Cyprus provide a cyclic record of changing depositional facies and sediment accumulation throughout the late Pleistocene, reflecting an alternation of wetter and drier periods.

It is well known that climatically induced events can produce sedimentary structures, which would typify those of a tectonically induced derivation. Small changes in regional rainfall have been documented to have a pronounced effect on river discharge (e.g. Frostick & Reid, 1989; Bartov et al., 2002). This is particularly the case in arid or semi-arid areas, such as Cyprus. I therefore hypothesize that the grain-size variations in the Vasiliko fans reflect altering patterns of discharge and sediment availability in response to climatic fluctuations. Three ‘wetter’ periods are identified as the conglomeratic units within AF1 and 2 (Fig. 4.6). Whilst it is controversial to suggest deposition during wetter periods where incision is expected and often documented (Owen et al., 1997; Mack & Leeder, 1999; Macklin et al., 2002; Pope & Wilkinson, 2005; Pope et al., 2008), recent work has shown alluvial fan deposition in arid and semi-arid areas of Central Iran and the Dead Sea, Israel was coincident with high lake-level periods during climatically wetter periods (Stevens et al., 2001; Bartov et al., 2002; Arzani, 2007). Frequent flooding, during a wetter climate regime, will lead to an increase in the total sediment flux, suggesting that the relationship between climate and sediment flux is more complex than a simple correlation between arid or humid climates (Jo et al., 1997). Palaeohydraulic and detailed architectural analysis of the Vasiliko fan deposits suggests streamflow deposition in relatively low efficiency rivers due to the presence of armouring (e.g. Laronne & Reid, 1993; Jones & Frostick, 2008). Bedload transport rates were lowered due to extensive armouring of the streambed, whilst abundant sediment supply (particularly in the two LCC) promoted aggradation in the river system (Jones et al., 2001; Frostick & Jones, 2002). This would explain the lack of incision in this fan system, which would be expected during a period of increased precipitation.

At the present day Cyprus is located within a semi-arid Mediterranean climate zone, influenced by the climatic patterns of Europe, North Africa and Asia (Bar-Matthews et al., 2000). Rainfall is strongly seasonal and largely restricted to the winter months in association with increased activity of depressions and the polar front.

Summer months are typically dry, influenced by the northwards displacement of the subtropical high-pressure belt from the North African deserts.

However, during precession minima when perihelion falls within the Northern Hemisphere summer an intensification of the North African and Indian Ocean (SW) monsoons and increased activity of summer Mediterranean depressions prevail. The consequence of this is an enhanced flux of freshwater into the eastern Mediterranean (Levantine Basin) (Rohling & Hilgen, 1991; Kallel et al., 2000) resulting directly in the formation of sapropels. These sapropels are considered to be associated with periods of increased freshwater runoff from the continent (Bar-Matthews et al., 2000) related to periods of high hydrological activity and have been shown to coincide closely with minima in the precession index (Rohling & Hilgen, 1991; Kroon et al., 1998; Bar-Matthews et al., 2003). However, the influence of the monsoon only reaches as far as the southern Sinai desert and though deemed responsible for increased discharge of the River Nile, cannot explain the increased humidity and associated precipitation in the northern borderlands of the eastern Mediterranean. It is proposed that the increased activity of the Mediterranean (summer) depressions, which tracked from the western part of the basin to the east picked up moisture along the way resulting in enhanced flux of moisture to the area and was superimposed on the increased monsoonal moisture flux from the southeast.

Speleothems from the Soreq and Peqiin caves in Israel also reveal evidence of wetter climatic conditions at precession minima when a marked decrease in $\delta^{18}O$ in conjunction with a significant increase in $\delta^{13}C$ is indicative of very wet conditions (Bar-Matthews et al., 2000, 2003). Kallel et al. (2000) similarly identified that low $\delta^{18}O$ values were correlated with periods of sapropel formation.

It is therefore proposed that wet periods are associated with increased intensity of the Indian Ocean (SW) monsoon resulting in enhanced discharge of the river Nile into the Levantine Basin (Fig. 4.1), which, coupled with increased activity of the summer depressions in the Mediterranean, brought enhanced precipitation into the eastern Mediterranean. The combination of both the monsoon and depression activity at precession minima increased the discharge of rivers in the eastern Mediterranean and is recorded in the Vasiliko fan system (LCC-1, LCC-2 and OFG's), in the Soreq and

Peqiin cave speleothems and as sapropels in the Levantine Basin. These events are correlatable to the alluvial fan succession described (Fig. 4.9).

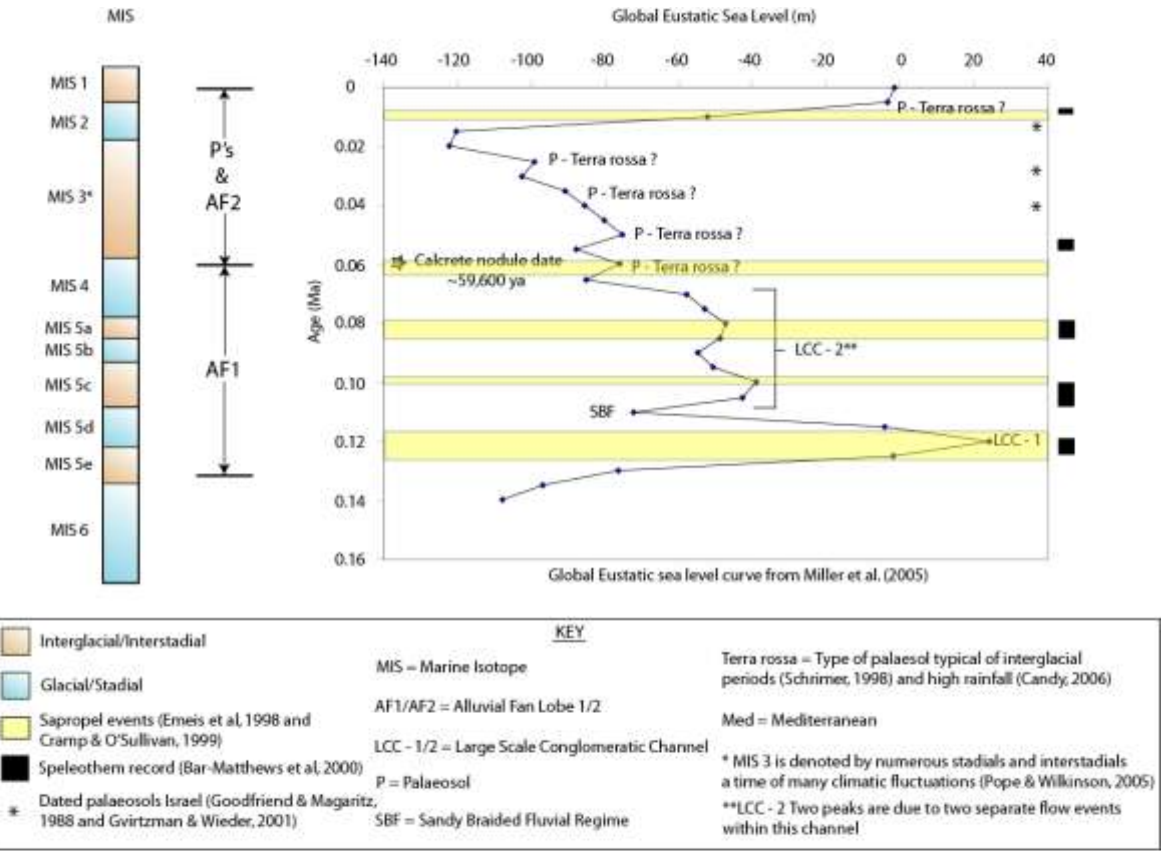


Figure 4.9 – 'Matching' of the Vasiliko fan succession to Pleistocene Marine Isotope Stages and eustatic sea level curve.

4.7 Conclusions

The Vasiliko alluvial fans of southern Cyprus provide a record of the spatial and temporal distribution of alluvial fan deposition and associated facies changes controlled by the precession paced climatic variations during the late Pleistocene.

Despite coeval (albeit reduced) tectonic activity the sedimentation of alluvial fans, adjacent to the Troodos Mountains, records distinct wetter and drier phases. I propose that the late Pleistocene Vasiliko fans record precessional scale changes in the facies architecture grain size variations, which can be correlated to the offshore sapropel record, palaeosol stratigraphy of the Negev desert and the climate proxy record of the Soreq and Peqiin Caves of Israel.

The climate models for the eastern Mediterranean provide an analogue to explain these correlations. During precession minima the North African and Indian Ocean SW summer monsoons intensified increasing the discharge of the River Nile. This provides the increased nutrient flux into the Levantine Basin, a requirement for the formation of the eastern Mediterranean sapropels. The influence of the Indian Ocean monsoon does not extend beyond the southern Sinai desert and therefore cannot explain the rainfall in Cyprus. Current models suggest that increased summer precipitation in the northern borderlands of the eastern Mediterranean (at precession minima and therefore times of sapropel formation) was likely due to increased activity of Mediterranean summer depressions, forming predominantly in the western Mediterranean (Rohling & Hilgen, 1991; Rohling, 1994). The increased runoff and associated flux of nutrients through the alluvial fans in southern Cyprus likely provided a significant addition to that which entered the eastern Mediterranean and resulted directly in sapropel formation offshore Cyprus.

It is therefore concluded that wetter/humid periods recorded in the Vasiliko alluvial fans in Cyprus correspond to precession minima and hence correlate with the offshore sapropel records and the wet periods deduced from speleothems in the Soreq and Peqiin Cave.

Chapter 5

Deciphering climatic controls on sedimentation in a tectonically active area, Cyprus

5.1 Motivation

The original motivation of this study aimed to reconstruct the tectonic and climatic controls on basin fills in Cyprus, with the primary objective to understand the uplift history of the supra-subduction zone to the south of the island. This was instigated to provide a test of subduction models, since current perspectives on how subduction zones inititate and become self-sustaining still remains relatively unclear. It was envisioned that by de-convolving the climatic controls on sedimentation through the evolution of the Cyprus 'fore-arc', that the residual record of tectonic uplift would be revealed. A task that would be achieved through employing sequence stratigraphical techniques, stable isotopic, palaeohydraulic and micropalaeontological analyses, and their subsequent correlation to global patterns. However, during analysis it became evident that climate played a dominant role in controlling the timing of sedimentary depositional systems and their internal architecture (cyclicity), leading to a re-consideration of the original objectives of the study. Sequence stratigraphy, where applied, was entirely explicable through glacio-eustatic changes in sea level, whilst palaeohydraulic analysis of Quaternary deposits indicated a cyclical connection with wet/dry events, correlating with reliable climatic proxies such as sapropel and speleothem records. Most notably, detailed foraminiferal analysis identified distinct warm and cool modes, providing the building blocks for explaining the climatic cyclicity within the deposits.

The location of Cyprus is imperative for the understanding of this study, for it is situated in a region sensitive to the interactions of both high latitude (Ferrel Cell, Northern Hemisphere Ice Sheets) and low latitude (Hadley Cell, Intertropical convergence zone) climatic effects (Fig. 5.1). Its lower mid-latitude, subtropical position (34-35˚N) is within the influence of a number of major climatic systems, on the fringes of the Indian and North African monsoonal systems, within the realms of the high latitude moisture bearing westerlies (central and northern Europe) and the low latitude, dry subtropical high pressure system (northern Hadley cell) over northern Africa (Rohling et al., 2009). These climatic boundaries oscillate on seasonal to orbital and geological timescales, however the resolution of this study could only detect those of an orbital tempo.

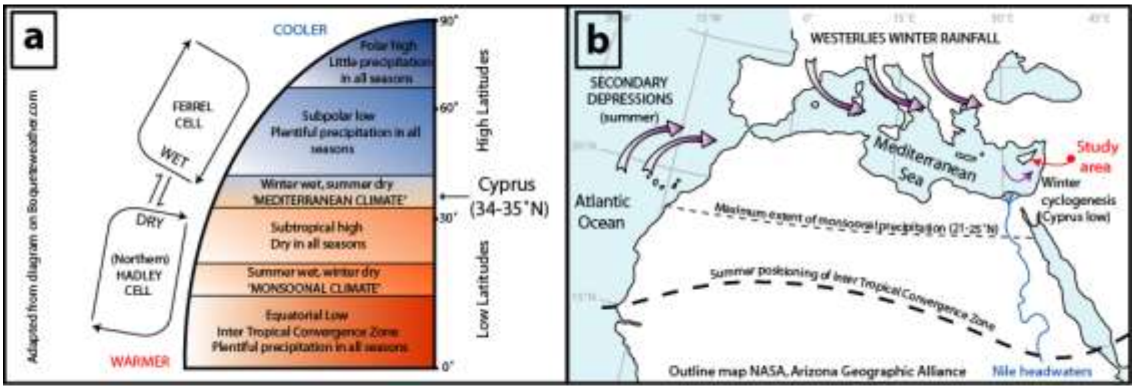


Figure 5.1 – ITCZ positioning and climatic systems influencing the eastern Mediterranean area.

This study focussed on the late Neogene and Quaternary, climatically dynamic periods in Earth's history, most importantly heralding the intensification of the Northern Hemisphere Ice Sheets (NHIS) and the Middle Pleistocene Transition (MPT). Episodic occurrences of NHIS's are thought to have been possible since ~25 mya (DeConto et al., 2008). However, long term permanency of the NHIS only initiated ~2.7-3.0 mya, coincident with a prominent step in global cooling and a downturn in atmospheric CO_2 (Pearson & Palmer, 2000; DeConto et al., 2008). Thus crossing the critical threshold below which major glaciations in the Northern Hemisphere occur (~280 p.p.m.v, DeConto et al., 2008).

In this study the link between North Atlantic climatic variability (ice volume) and its effect on climate belts influencing the eastern Mediterranean is tested. Climate modeling and geologically based palaeoclimatic observations indicate latitudinal temperature gradient (insolation) and ice volume effectively govern the positioning of the intertropical convergence zone (ITCZ). Thus impacting upon the location and intensity of the associated Hadley cell circulation (Rind, 1998; Lu et al., 2007; Armstrong et al., 2009) and the mid-latitude westerlies. During cold periods in the Northern Hemisphere the ITCZ is displaced in a southerly direction, whilst the converse applies during warm phases (Chiang et al., 2003; Broccoli et al., 2006; Yancheva et al., 2007). It is therefore hypothesised that orbitally induced north-south shifts in climate belts were responsible for governing the cyclicity in sedimentary architecture of the late Neogene and Quaternary basins of Cyprus. The progressive expansion of the NHIS may have provided an underlying long-term (geological) control on depositional systems.

5.1.1 Relevant geological framework

Cyprus lies within the Levantine Basin, to the north of the active Cyprus supra-subduction zone, where the present day boundary between the converging African and Eurasian plates is found (Fig. 1.1). The island has a history of tectonic uplift, exemplified by the presence of the oceanic crustal sequence of the Troodos Massif, the highest point of which is denoted by Mount Olympus (1951 m a.p.s.l.). A rapid phase of uplift during the latest Miocene in association with the initiation of the northwards dipping subduction zone (Orszag-Sperber et al., 1989; Poole & Robertson, 1991; Robertson et al., 1991; Eaton & Robertson, 1993; Stow et al., 1995; Schirmer, 2000; Davies, 2001) and approximately 2 km of uplift since the latest Pliocene to earliest Pleistocene (Eaton & Robertson, 1993; Stow et al., 1995; Schirmer, 2000; Davies, 2001), has provided the relief and source necessary for the construction of the clastic depositional systems studied. During the Pliocene through to the Quaternary a general pattern of regression is recorded in the sedimentary succession of the ‘fore-arc’. Shelfal shallow marine silts dominating the Pliocene are replaced by marginal marine fan delta deposits and culminate in Quaternary terrestrial alluvial fans and marine terraces. A record of island-wide raised beaches at heights 100-110m, 50-60m, 8-11m and <3m suggest uplift of the region was episodic (Poole et al., 1990; McCallum & Robertson, 1995) or they formed as a result of climatically induced eustacy.

5.1.2 Climatic setting of Cyprus: Present and Past

The Mediterranean climate is characteristically typified by mild, wet winters and warm, dry summers (Fig. 5.1a; Giorgi & Lionello, 2008; Rohling et al., 2009), a climatic regime currently under the influence of summer insolation minima when aphelion falls in boreal summer (Rohling et al., 2009). In the summer the northerly migration of the ITCZ brings the Mediterranean under a high pressure regime, attributable to the descending portion of the northern Hadley cell, thus leading to dry conditions principally over the southern Mediterranean (Fig. 5.1a, Cramp & O’Sullivan, 1999;

Giorgi & Lionello, 2008; Tzedakis et al., 2009). Conversely a southerly deflection allows mid-latitude westerlies and winter cyclogenesis to be established (Cramp & O'Sullivan, 1999; Fischer et al., 2009; Rohling et al., 2009; Tzedakis et al., 2009). Minor shifts in the atmospheric cells combined with the confined basinal configuration of the Mediterranean Sea generate a sensitivity of the area to climatic modifications (Rohling et al., 2002, Giorgi & Lionello, 2008; Tzedakis et al., 2009). This sensitivity is recorded in many depositional systems across the eastern Mediterranean (e.g. Weltje & De Boer, 1993; Kroon et al., 1998; Van Vugt et al., 1998; Wehausen & Brumsack, 1999; Lourens et al., 2001).

Throughout the Pliocene and Quaternary, variations in two main climate systems influenced the eastern Mediterranean: i) cyclical growth and decay of the NHIS under orbital influence and, ii) the consequent north-south positioning of the ITCZ and associated climate belts. The rapid expansion of the NHIS ~2.7 to 3.0 mya (Maslin et al., 1998; Willis et al., 1999; Ravelo et al., 2004; Miller et al., 2005; Lisiecki & Raymo, 2007), dominantly affected the high latitudes and was predominantly paced by the orbital parameter of obliquity between ~2.9 and 0.8 Mya (Maslin et al., 1998; Willis et al., 1999; Marlow et al., 2000; Miller et al., 2005). Thereafter the amplitude of the glacial-interglacial variations became larger (Larrasoaña et al., 2003) dominantly modulated by short eccentricity. This transition in pacing from 41 kyr to 100 kyr driven ice sheet variation (widely referred to as the Middle Pleistocene Transition) is thought to have been induced by a critical ice sheet mass threshold, although is unequivocally resolved (Maslin & Ridgwell, 2005; Lisiecki & Raymo, 2007; Drysdale et al., 2009). A modification in the climate system from a linear to non-linear response to orbital forcing is generally considered foremost (Clark et al., 1999), with the role of internal feedbacks increasingly taking precedence (see Maslin & Ridgwell, 2005 for detailed review).

The intensification of the NHIS promoted a long-term cooling and progressive lowering of sea level throughout the Plio-Pleistocene. Within this long term cooling orbital oscillations in ice volume occurred promoting shifts in climate belts. Warmer periods were likely represented by the dominance of summer conditions, whilst cooler periods reflected dominance of the current winter conditions. However, two summer modes are possible depending upon orbital configurations, i) a summer aphelion phase, such as the present day and, ii) a summer perihelial phase, last experienced ~8-10 kya. Both phases occur during northerly shifts in the ITCZ when dominance of the descending northern Hadley Cell occurs. Climatic observations indicate northerly shifts during the perihelial phase are coeval with a strengthening of both the north African and Indian (SW) summer monsoon (Tuenter et al., 2003; Fischer et al., 2009), when summer insolation thresholds above 470 W/m^2 are achieved (deMenocal et al., 2000). The monsoons do not directly impact upon the eastern Mediterranean climate (simply influencing the discharge of the River Nile and resulting sapropel stratigraphy in the Levantine Basin), as their precipitation belts extend no further than 21-25˚N and 30˚N respectively (Fig 5.1b; Mandell & Simmons, 2001; Rohling et al., 2002; Gupta et al., 2003; Tzedakis et al., 2009). However, an understanding of intensifications in the summer monsoons is imperative as they are considered to be concomitant with the development of Atlantic born, western Mediterranean summer cyclogenesis (Rohling & Hilgen, 1991; Rohling, 1994; Scrivner et al., 2004; Akçar & Schlüchter, 2005). The latter creates a wet summer signature across the eastern Mediterranean (Fig. 5.1b) and adds to the development of sapropels in the Levantine Basin. To what extent are these forcing factors recorded in the sedimentary succession of Cyprus?

5.2 Depositional sequence history of Cyprus: Evidence

The early Pliocene (Zanclean) to late Pleistocene (Upper) sedimentology of southern Cyprus is composed of three main depositional systems, all exhibiting cyclic deposition. Time slices and the cyclical depiction of each depositional system are illustrated in Figures 5.2 and 5.3.

5.2.1 Depositional System 1 (DS1) - early Pliocene to early Pleistocene

This is the oldest sequence in the study and is represented by a shallowing upwards succession of foraminifera enriched, shelfal, grey clayey silts. The study (Chapter 2) focussed on the uppermost part of the stratigraphy where, i) a remarkable correspondence of the cyclicity to the obliquity controlled sea level variations has been recognised and ii) microfaunal analysis identified transitions in climatic modes, reflecting both global and local controls (between ~1.8 and 2.1 myrs, *G. inflata* and *G. cariacoensis* biozones).

Foraminiferal assemblages exhibit distinctive changes in assemblage characteristics, between the upper and lower part of the studied stratigraphy, with notable variations identified between the northern and southern localities. These trends

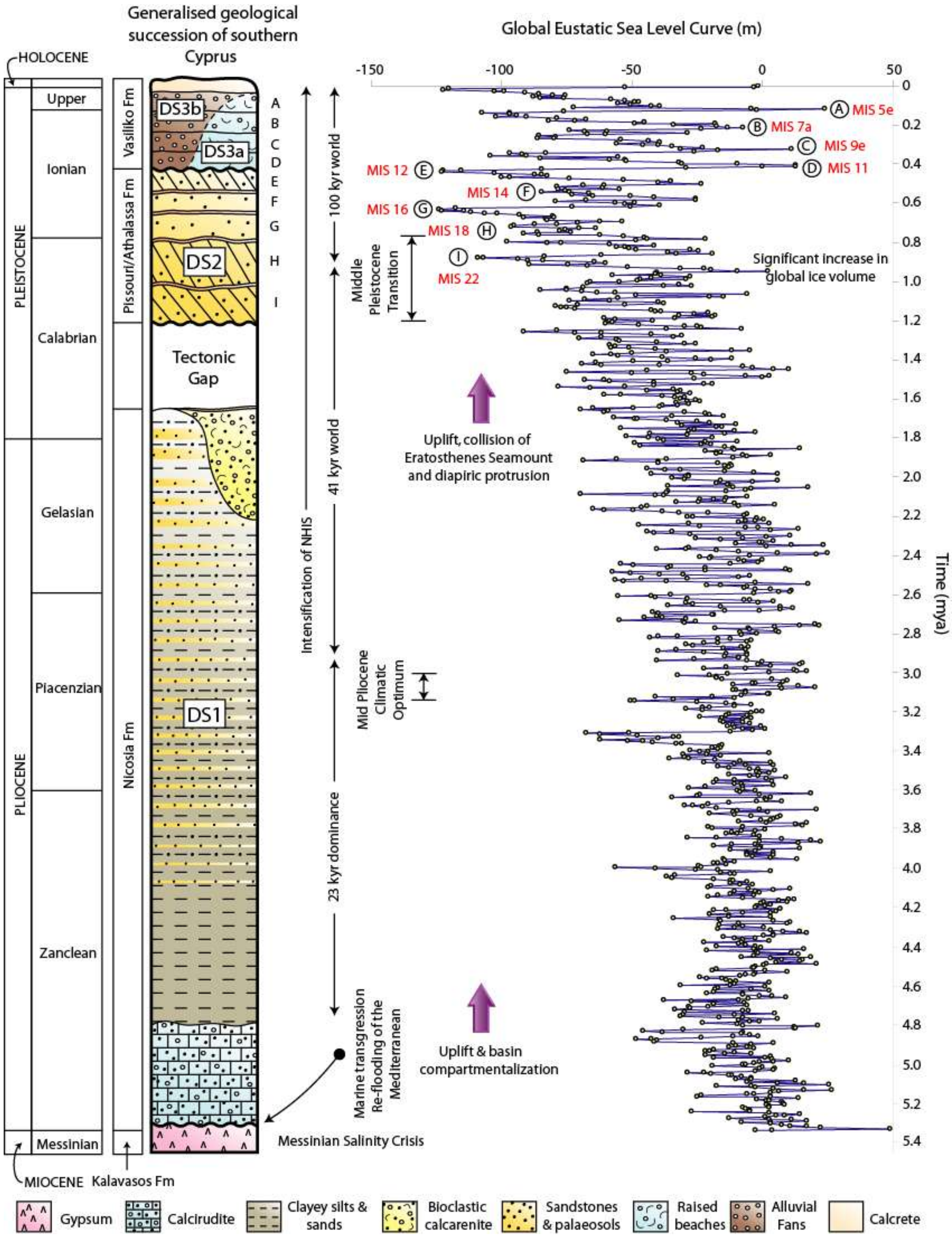


Figure 5.2 – Depositional systems in the late Miocene to Recent geological record of southern Cyprus and their correlation to global climatic events

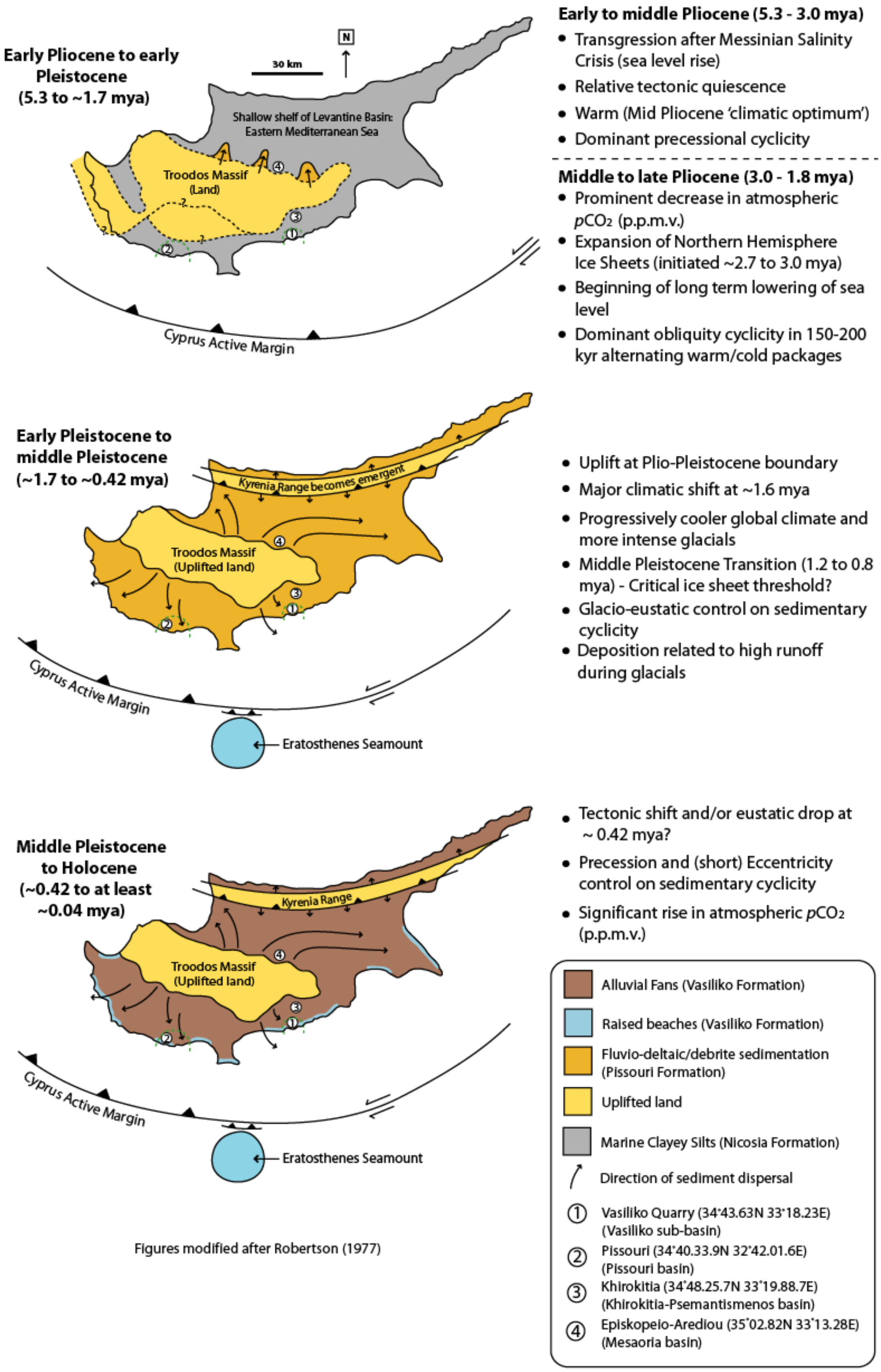


Figure 5.3 – Sedimentary evolution of the Pliocene to Holocene Cyprus 'fore-arc' succession

are depicted on Figure 5.4. In terms of temperature both the northern and southern planktonic species indicate a transition from cooler to warmer climes in the uppermost part of the Nicosia Formation. However, a disparity in localised controls (precipitation), represented by the benthic community indicates that the south is much wetter than the north during the cooler phase. A signature reflected through the abundance of species

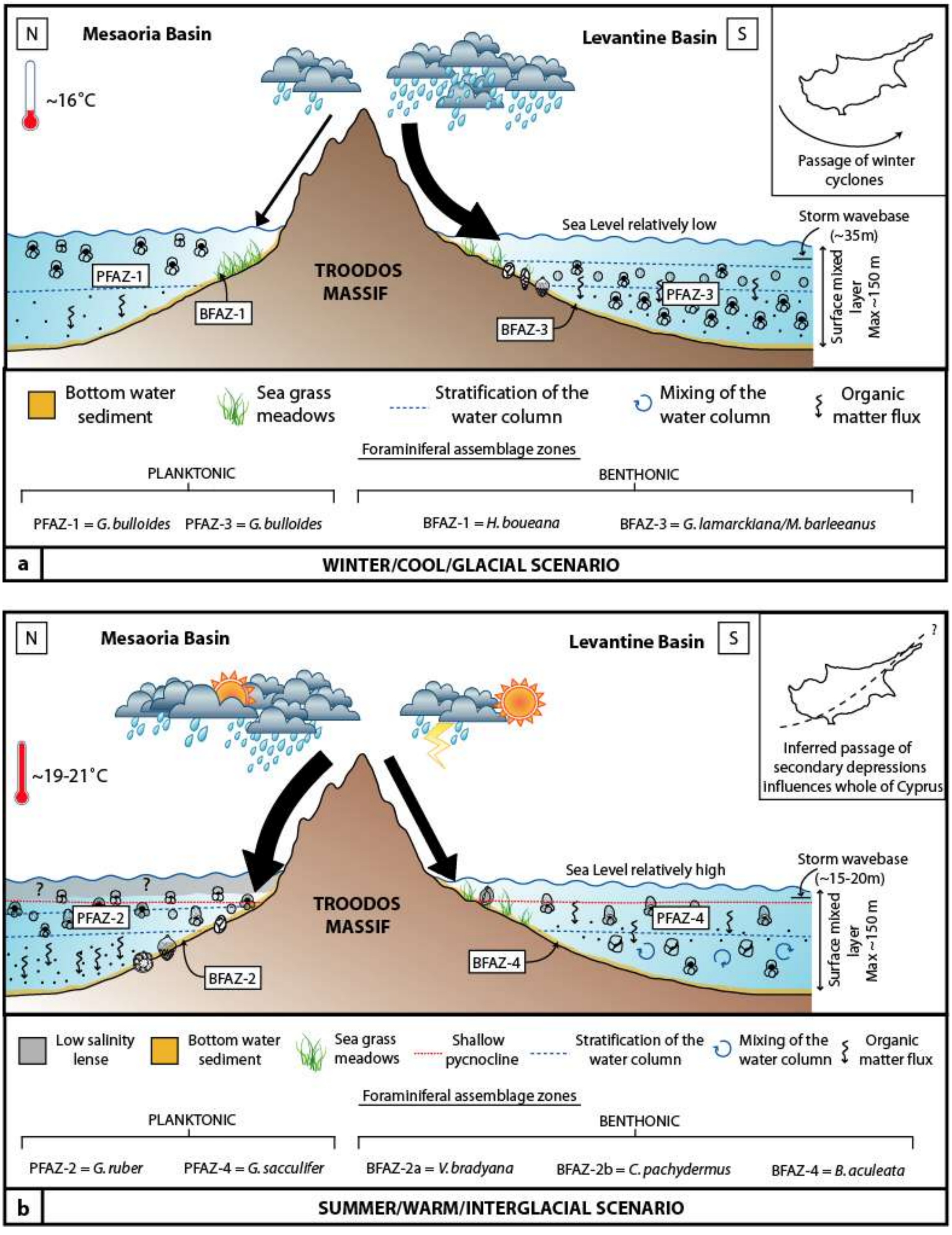


Figure 5.4 – Climatic conditions and associated foraminiferal assemblages in northern and southern Cyprus during the Plio-Pleistocene

tolerant to organic matter flux and the lack of epiphytic taxa. During the warm phase both localities carry a significant freshwater influx signature (enhanced precipitation). Based upon the above variances in the assemblages two coupled atmosphere-ocean state end members can be recognised: i) cool, wet and dominantly eutrophic (Fig. 5.4a), ii) warm, wet and mixed oligotrophic/eutrophic (Fig 5.4b). The ‘cool’ end member is comparable to the present day winter mode, whilst the ‘warm’ end member is reflective of perihelial summer conditions when Mediterranean summer cyclogenesis prevails. From this analysis it can be determined that two scales of cyclicity are embodied within these deposits: i) small-scale obliquity variations that appear to correlate with the onset of the NHIS and, ii) larger scale (~150-200 kyr, three to four obliquity cycles) temperature fluctuations identified through foraminiferal analysis and their time constrained correlation to the eastern Mediterranean oxygen isotope and Northern Hemisphere insolation records (Chapter 2).

Faulting and the incision of bioclastic calcarenites (Pissouri) and debrites (Khirokitia) into the upper part of the formation indicate probable tectonic uplift at the Plio-Pleistocene boundary (Houghton et al., 1990; Robertson, 1998; Stow et al., 1995), which terminated DS1. The increase in sand content up section and appearance of a shallow marine macrofauna infers shallowing (and hence eustatic sea level fall) was coeval with uplift, in agreement with the interpretations of Robertson (2000), Davies (2001) and Stow et al. (1995).

5.2.2 Depositional System 2 (DS2) - early Pleistocene to mid Pleistocene

A series of eight facies have been identified ranging from bioclastic carbonaceous and calcarenitic facies, to medium to coarse-grained cross-bedded sandstones and Terra Rossa palaeosols. A cyclic mode of deposition has been identified, reflected in metre scale shallowing upward packages containing a basal sandstone and an overlying palaeosol (Fig. 5.2). The development from delta front facies at the base through to upper delta plain deposits at the top indicates the succession became successively more proximal through its evolution. A total of six sequence boundaries have been identified, five of which correlate with glacial maxima (MIS 22, 18, 16, 14 and 12), reflected in the repetitive preservation of the lowstand systems tract and systematic correlation with sea level oscillations (Chapter 3).

The system is interpreted to have initiated as a wave and storm dominated shoreface delta system, partially contemporaneous with the Nicosia Formation, coeval with documented uplift and a precursor to the fluvially influenced braided sandstones. A disconformity is inferred between the storm, marine dominated and overlying fluvio-deltaic facies. Fluvio-deltaic deposition instigated ~0.88 mya (start of MPT), coincident with a marked increase in sediment supply (related to pluvial conditions during glacials) throughout European river systems, and concurrent with a significant increase in global ice volume (Head & Gibbard, 2005). In conclusion, a shallowing upwards and progradational succession has been identified within a long-term regressive regime, where glacio-eustatic variations on a 4^{th} order, (short) eccentricity periodicity (~100 kyr) and hence climatic control on deposition has been inferred. This succession is constrained by deposits of DS3a and DS3b implying termination of fluvio-deltaic deposition prior to 0.42 mya.

5.2.3 Depositional System 3 (DS3) - mid to late Pleistocene

Two coevally occurring depositional systems comprise this composite succession, consisting of a) raised beaches and b) alluvial fans. A distinctive four-terrace morphology defines these deposits across Cyprus (Chapter 4, Appendix F), with the youngest fans correlating with the raised beach terraces (Poole et al., 1990).

***DS3a*:** These deposits are generally characterized by coarse bioclastic grainstones containing rounded Troodos clasts and an abundance of intact and/or fragmented shells. The raised beaches occur at heights of <3, 8-11, 50-60 and 100-110 metres above sea level (m.a.s.l.), with the lowermost beaches at <3 and 8-11 m.a.s.l. dated by Poole & Robertson (1991) at 116-134 kya and 185-204 kya respectively. These younger beaches punctuate the mid- to late Pleistocene sedimentary record with a ~100 kyr (short eccentricity) reoccurrence time, concomitant with the pronounced interglacials MIS 5 and 7 (supported by the presence of interglacial fauna such as *Strombus Bubonious*; Poole & Robertson, 2000). The older, as yet undated raised beaches are by inference regarded to similarly correlate with preceding significant interglacials (MIS 9 and MIS 11), following the ~100 kyr rhythm.

***DS3b*:** Alluvial Fans comprise this succession in conjunction with prominent palaeosol horizons. The fans studied throughout southern Cyprus, with particular reference to the type section at Vasiliko Quarry show clear cycles in their coarse (conglomeratic) and fine components (sandstones) (Waters et al., 2010 and Appendix F). A detailed palaeohydrological and architectural study on the late Pleistocene Vasiliko fan reveals a linkage between the cyclic transitions in facies and climatic conditions (Waters et al., 2010). Conglomeratic channels represent wet conditions, whilst braided sandstones reflect drier conditions. A precessional (23 kyr) control has been attributed to the cyclicity, where wet/humid periods recorded in the fans correspond to minima in the precession index, when activity of Mediterranean secondary depressions in the summer is enhanced. These precessionally paced periods of increased runoff demonstrate a linkage with offshore sapropels in the Levantine basin, correlate with wet periods in speleothem records (Israel) and exhibit an alliance with palaeosol stratigraphy in the Negev desert.

It is predicted that DS3a and the onset of each DS3b is responding to the 100 kyr eccentricity signal, deposited synchronously and providing a chronology of significant interglacials, identifiable with a glacio-eustatic control. The internal architecture of each alluvial fan is interpreted to be responding to a precessional control. If a significant phase of uplift is marked by alluvial fan deposition (Fanglomerates) as Poole & Robertson (1991) suggest, then this phase should be placed ~0.42 mya, based on the above theories.

5.3 Cyclical sedimentation: alternative hypotheses

It may be argued that the cyclicity documented in the depositional systems (section 5.2) could be the product of mechanisms other than climate, such as tectonics and/or autocyclicity. These alternative controls similarly impact upon the production of sedimentation, the rate at which sediments are deposited and the resulting architectural pattern (an overview is given in Chapter 1, and Chapter 3, section 3.5). However, tectonics and autocyclicity have been ruled out as dominant contributors to the cyclicity identified in DS1, DS2 and DS3, reasons for which are detailed in Chapters 2, 3 and 4 and summarized as follows:

i) Cycles have been identified and correlated across several basins in Cyprus, many of which are inferred to correlate with Mediterranean wide contemporaneous deposits. This suggests autocyclicity was not the mechanism responsible for their resulting architecture, since these controls are intrinsic to the depositional system and therefore would not translate across physically large scales. It is not disputed that autocyclic mechanisms may have had a role to play, however their differentiation is only evident within the cycles (e.g. Facies $A_{3,}$ Chapter 3, Section 3.6.1) and not as any direct cause for the cyclicity.

ii) Episodic tectonic movements are known to induce rhythmic deposition of sediments. However, it would be expected that features typical of structurally unstable regimes would accompany such an interpretation, perhaps in the form of syn-depositional faulting, deformation structures, abrupt facies changes and/or angular unconformities between successive cycles. These features are rare to absent within the successions, only occurring between major changes in depositional regime as detailed in section 5.2.

Most importantly, biostratigraphical tie points provide a basic temporal framework in which to correlate depositional cycles to the global eustatic sea level curve and the known climatic history. An understanding of the sedimentary structures, changes in foraminiferal assemblages and palaeohydraulic analysis have enabled these correlations to be explained through a dominantly climatic control.

5.4 Eastern Mediterranean Plio-Pleistocene climatic reconstruction: Discussion

Palaeoclimatic reconstructions indicate there is a fundamental link between the fluctuations in North Atlantic climate variability (size of NHIS) and boreal climate systems such as the mid latitude westerlies, Indian and north African monsoons (Gupta & Thomas, 2003; Gupta et al., 2003; Hong et al., 2003; Larrasoaña et al., 2003) and Mediterranean summer cyclogenesis (Rohling, 1994; Alpert et al., 2006). The strength of these phenomena depends upon the latitudinal positioning of the ITCZ and the dynamics of the interconnected Hadley cells (Dima & Wallace, 2003; Wang, 2009). Importantly, these systems are sensitive to both the orbital parameters of the Earth (Wang, 2009) and interhemispheric temperature contrasts (Rind, 1998; Broccoli et al.,

2006) linked to ice volume changes (Armstrong et al., 2009) and atmospheric CO_2. It is therefore hypothesised that the regular cyclicity identified within DS1, DS2 and DS3 is attributable to the systematic variations in the NHIS.

When precession places aphelion in boreal summer, obliquity is low (minimal tilt) and eccentricity is elongating the summer Earth-Sun distance, an orbital configuration conducive for maximal ice sheet growth is produced (Maslin & Ridgwell, 2005; De Conto et al., 2008). This 'cool mode' configuration has a profound effect on the ITCZ, displacing it in a southerly direction (Chiang et al., 2003; Broccoli et al., 2006; Yancheva et al., 2007). Conversely, a period of significant ice ablation (warm mode) is characterized by high eccentricity and obliquity, in conjunction with minima in the precession index when perihelion coincides with boreal summer (Elkibbi & Rial, 2001; Tuenter et al., 2003). Thus promoting a northerly shift in the climate belts.

These cool and warm modes have been recognised in the coupled atmosphere-ocean end members deduced from foraminiferal analysis and wet/dry cycles of DS2 and DS3b. It is concluded that the meridional movements of the ITCZ and associated climatic belts, in response to orbital ice volume, were the dominant control of sedimentation in Cyprus. During boreal summer Atlantic born Mediterranean depressions prevail (Fig. 5.5a). However, when the Northern Hemisphere is very cool a winter regime comparable to the present day pertains (section 5.1.2, Fig. 5.5b).

A number of different timescales impact upon this monotonic north-south oscillatory pattern. For example the expansion of the NHIS to the present has imposed a long-term (geological) cooling, gradually deflecting the ITCZ in a southerly direction by ~2˚ (Lyle et al., 2002). The greatest impact, however, is exemplified in the internal cyclicity within the deposits, which appear to be products of shorter term orbitally controlled shifting of the ITCZ and atmospheric cells. Prior to the MPT small-scale obliquity controlled ice volume variations occurred in discrete alternations of warmer and cooler periods (each package is composed of 3 or 4 obliquity cycles). After the MPT (~0.8 mya) thicker ice sheets promoted distinct glacial-interglacial variations on a short eccentricity timescale (~100 kyr). A transition identified in DS2 where ~100 kyr cyclicity is evident and a 'saw tooth geometry' appears within proxy records (Fig. 5.6). The 100 kyr glacial-interglacial variability is considered to be defined by every 4/5th precession cycle, with eccentricity modulating the amplitude envelope of precession (Maslin & Ridgwell, 2005). Recent debate suggests 'skipped' obliquities may now be the primary control on the 100 kyr variability (e.g. Huybers, 2007; Drysdale et al., 2009), I however, consider the precessional variations to be strongly evident within DS3b, as explained below.

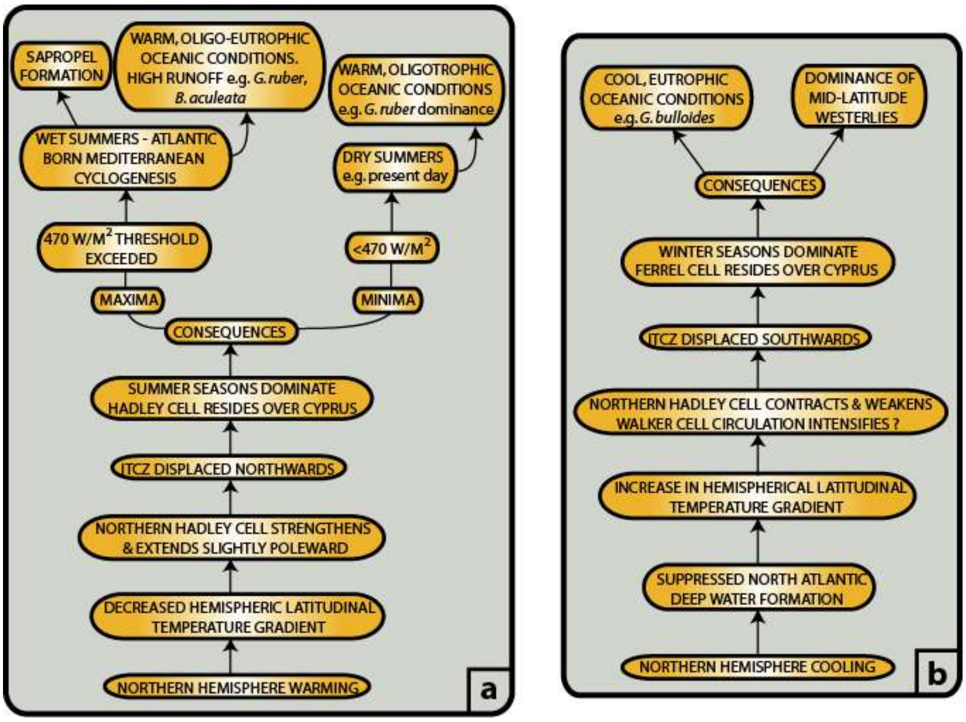


Figure 5.5 – Eastern Mediterranean climatic response to Northern Hemisphere warming and cooling

5.4.1. The importance of atmospheric CO_2 on mid to late Pleistocene climate

Strong precessional control on sedimentary architecture in Cyprus has only been observed within the last ~ 420 kyr, reflected within DS3b. This is consistent with numerous proxy records (e.g. CH_4 and CO_2) where supremacy of the precessional component has been recognized, even at higher latitudes during the summer (e.g. Ruddiman, 2001; Tzedakis et al., 2009). It is considered that CO_2 and CH_4 maxima potentially amplified orbital forcing on a precessional-scale and enhanced ablation driving the interglacial state. According to ice core records there is a notable increase in pCO_2 ~ 420 kyr when the >280 p.p.m.v. threshold value was surpassed for the first time since the intensification of the NHIS (Petit et al., 1999; Siegenthaler et al., 2005; Hönisch et al., 2009). Intense and rapid deglaciation during interglacials has since been documented (see Petit et al., 1999 for review). Thus indicating the ~ 420 kyr event was a critical period, potentially reflecting the establishment of significant NHIS melting and the dominance of low latitudinal precessional scale climatic variability.

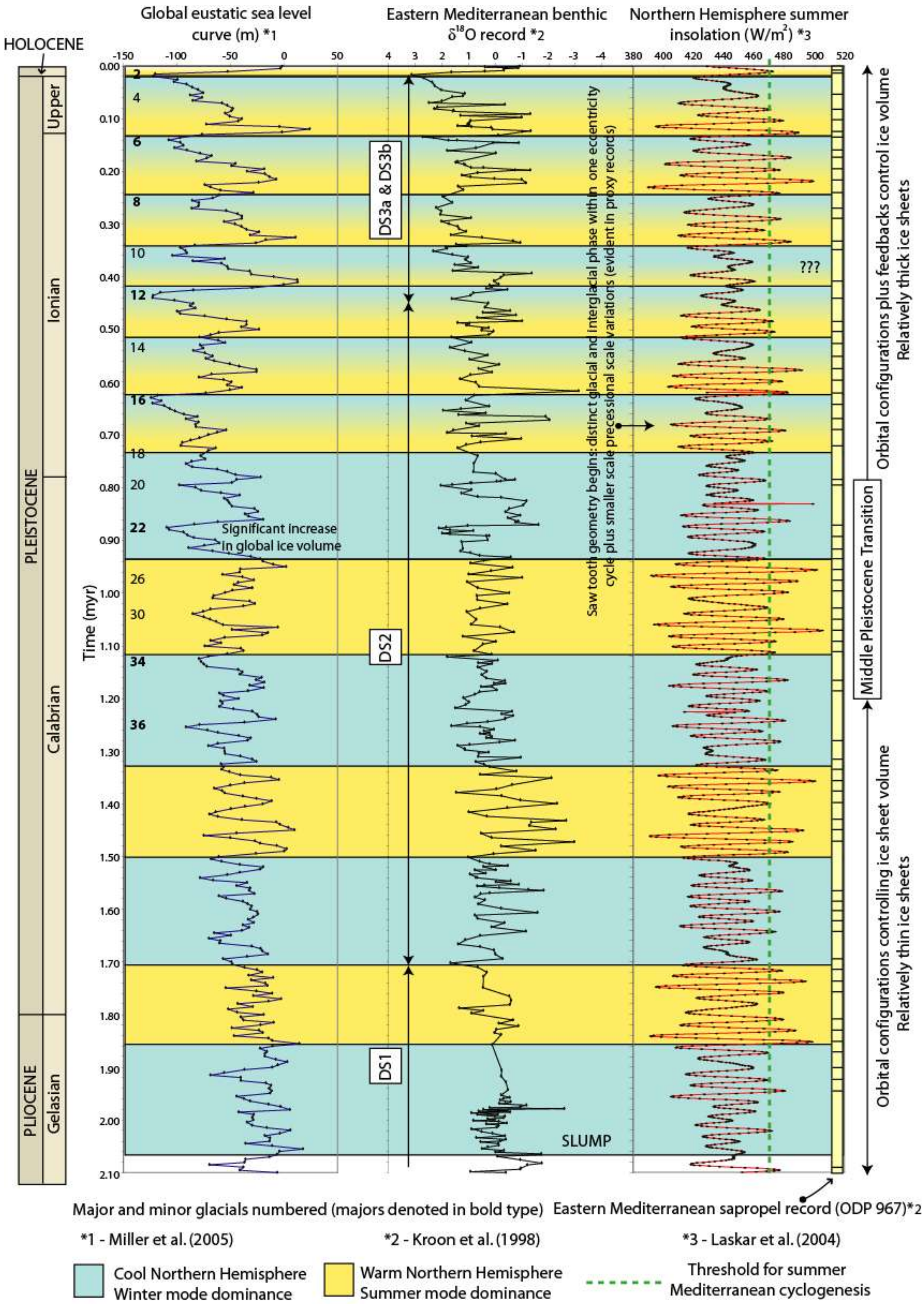


Figure 5.6 – Detailed studies in Cyprus and their relation to climatic perturbations throughout the Plio-Pleistocene

5.5 Conclusions

Palaeohydraulic reconstructions, lithological, micropalaeontological and architectural analysis have helped to elucidate the mechanisms controlling the cyclicity on sedimentation in Cyprus. The evidence presented in this study indicates the sedimentary evolution of the Cyprus 'fore-arc' responded to the progressive development of the NHIS and the movements of the ITCZ. An overall lowering of sea level from the mid-Pliocene to Present, promoted a long-term regression and an overall shallowing upwards sequence. This is exemplified through the propagation of the depositional systems from the marine (DS1) to marginal marine realm (DS2 & DS3a), culminating in a fluvial and terrestrial regime (DS3b). Despite the tectonic history of the island only two periods of major uplift have been identified in this study, the late Miocene (basin compartmentalization and the first occurrence of Troodos material within sedimentary successions) and the Plio-Pleistocene boundary (faulting in uppermost Nicosia Formation and shift in depositional systems coeval with eustatic sea level lowering). A third may have been possible just prior to the onset of DS3 ~0.42 mya, based upon the potential linkage of uplift and the instigation of alluvial fan deposition suggested by Poole & Robertson (1991).

This analysis suggests changes in ice volume affected the positioning and dynamics of the ITCZ and associated atmospheric cells, represented here on both geological and orbital timescales. The critical location of Cyprus residing between the oscillatory atmospheric cells (Fig. 5.7) has allowed the recognition of distinct phases of warming (general ice ablation, Hadley Cell and summer dominance) and cooling (ice expansion, Ferrel Cell and winter dominance). These transitions were reflected in the hydrographic reorganization of the oceanographic regime and through runoff phases in clastic systems.

It is acknowledged that tectonics played an important role in creating the relief and source necessary for deposition, amongst producing gaps and promoting shifts in depositional systems. However, I believe climate to be the overriding control on internal architecture within the disconformity bounded successions. These observations imply clastic sedimentary systems are effective archives for determining past climatic perturbations even in tectonically active areas, a fact which is becoming more widely accepted in current literature.

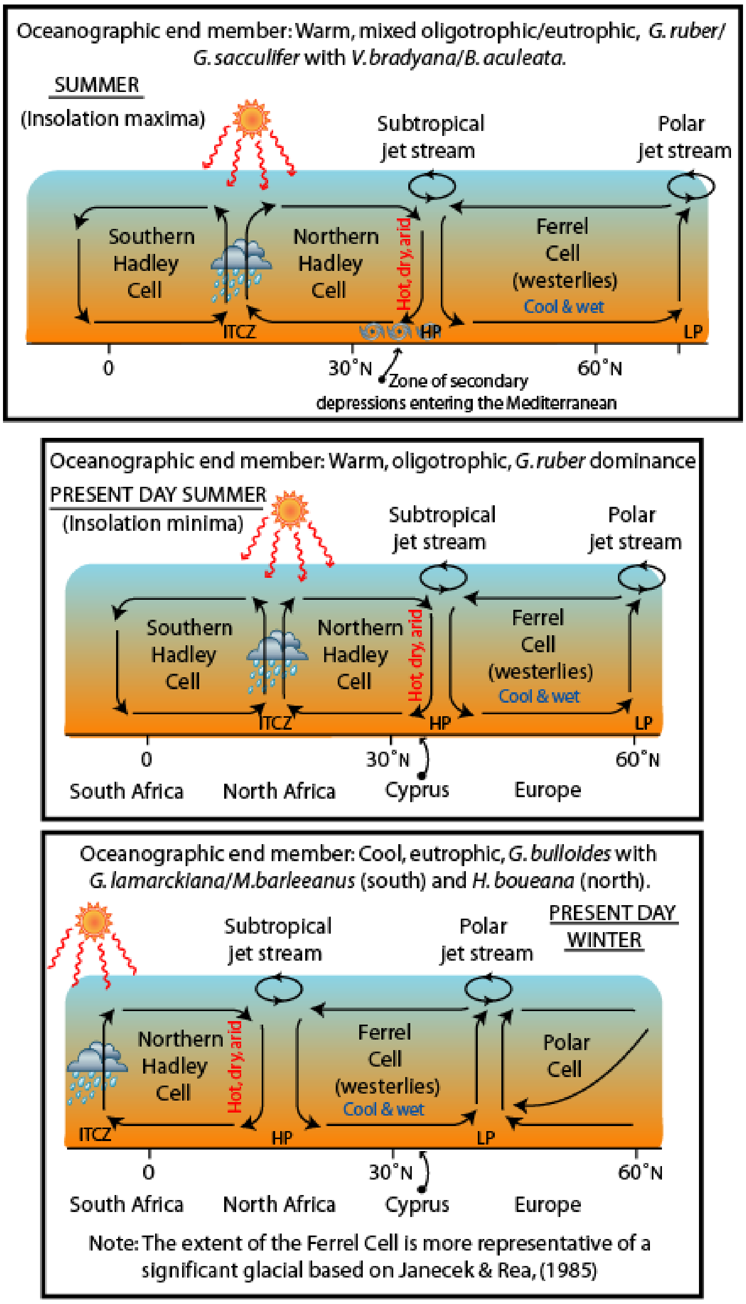


Figure 5.7 – Atmospheric cells influencing the eastern Mediterranean during the respective seasons

5.6 What climatic conditions should the eastern Mediterranean expect in the future?

It is common knowledge that ice sheets are rapidly melting in the Northern Hemisphere, where the >280 p.p.m.v. atmospheric CO_2 threshold is being regularly surpassed (De Conto et al., 2008). Such values are considered unfavourable for the continued development of Northern Hemisphere Glaciation, inducing a rise in temperature.

Climate model predictions for the Mediterranean indicate that by the end of the twenty-first century surface temperatures will increase by up to 4-6˚C (Alpert et al., 2008; Giorgi & Lionello, 2008; Hertig & Jacobeit, 2008), a rise closely associated with increasing global pCO_2. These concentrations are projected to attain levels that were last encountered in the 'mid-Pliocene climatic optimum' (Jansen et al., 2007; Haywood et al., 2009), an epoch frequently invoked as a 'greenhouse world' (Raymo, 1994), with global temperatures elevated by as much as 3˚C with respect to modern values (Ravelo et al., 2004; Raymo et al., 2006). The geological record of the eastern Mediterranean and palaeoclimatic interpretations suggest sedimentary deposition prior to the NHIS (with particular reference to the Mid-Pliocene warm period) fundamentally responded to low latitude precession variations e.g. Van Vugt et al. (1998). It was a period dominated by strong summer Mediterranean cyclogenesis and boreal summer monsoon activity, with long seasonal duration (Gupta et al., 2003; Gupta & Thomas, 2003; deMenocal & Rind, 1993).

Given the projected rise in pCO_2, the NHIS will continue to contract and glaciation will become increasingly unipolar (Antarctic ice sheets require a much higher CO_2 threshold for deglacial processes, see De Conto et al., 2008). As a consequence the ITCZ will shift away from the hemisphere with imposed ice cover (Chiang & Bitz, 2005) i.e. the Southern Hemisphere, and would adopt a more stable northerly position. The Hadley Cell (low latitude precessional control) will likely become a more permanent feature over the eastern Mediterranean, especially considering the anticipated ~4˚ widening of the atmospheric cell per degree of warming (Lu et al., 2007). This would be expected to induce a drying over the area. However, if the projected climatic changes revert to a climatic mode akin to the mid-Pliocene, then I anticipate the climate will not only become warmer (stronger insolation) but also wetter, drawing comparison with i) climatic conditions prior to the intensification of the NHIS and ii) the warm modes identified in this study. This long-term projection for the Mediterranean climate is consistent with numerous climatic studies, which similarly speculate a strong precipitation impact (increase in rainfall) on the mid-latitudes and eastern Mediterranean e.g. Rind (1998), Arz et al. (2003) and Barreiro et al. (2006).

APPENDIX A – Percentage abundances of identified foraminiferal species

	2.5 m		2.0 m		1.5 m		1.0 m		0.5 m	
	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage
Planktonic Foraminifera										
Globigerinoides ruber	18.67	54.73	17.67	20.94	16.61	21.14	32.77	34.37	20.67	28.97
Globigerinoides tenellus	3.86	11.32	12.43	14.73	17.25	21.95	12.51	13.12	0.00	0.00
Globigerinita glutinata	2.58	7.56	9.16	10.85	7.03	8.95	2.98	3.13	3.33	4.67
Globigerina bulloides	2.58	7.56	12.43	14.73	5.11	6.50	6.55	6.87	6.00	8.41
Orbulina universa	1.93	5.66	1.31	1.55	0.64	0.81	6.55	6.87	6.00	8.41
Globigerina rubescens	1.29	3.78	15.05	17.83	17.88	22.76	18.47	19.37	9.33	13.08
Turborotalia quinqueloba	0.64	1.88	0.00	0.00	0.64	0.81	1.79	1.88	0.00	0.00
Orbulina bilobata	0.64	1.88	0.65	0.77	1.92	2.44	0.60	0.63	0.00	0.00
Globigerina siphonifera	0.64	1.88	3.27	3.87	3.83	4.87	0.60	0.63	4.67	6.55
Globigerinita glutina	0.64	1.88	6.54	7.75	2.55	3.25	1.19	1.25	8.00	11.21
Globigerinoides sacculifer	0.64	1.88	1.31	1.55	2.55	3.25	0.60	0.63	8.00	11.21
Neogloboquadrina dutertrei	0.00	0.00	1.31	1.55	0.00	0.00	0.00	0.00	0.00	0.00
Globorotalia inflata	0.00	0.00	0.00	0.00	0.00	0.00	6.55	6.87	4.67	6.55
Orbulina sutularis	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.63	0.00	0.00
Calida calida	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.63	0.00	0.00
Globorotalia scitula	0.00	0.00	0.65	0.77	0.00	0.00	0.00	0.00	0.67	0.94
Globorotalia anfracta	0.00	0.00	0.00	0.00	0.64	0.81	0.60	0.63	0.00	0.00
Neogloboquadrina sp. (Left coiling)	0.00	0.00	0.65	0.77	0.00	0.00	0.00	0.00	0.00	0.00
Neogloboquadrina pachyderma	0.00	0.00	1.31	1.55	0.64	0.81	0.00	0.00	0.00	0.00
Globigerina borealis	0.00	0.00	0.65	0.77	1.28	1.63	2.38	2.50	0.00	0.00
TOTAL	**34.11**	**100.01**	**84.39**	**100.00**	**78.57**	**100.00**	**95.34**	**100.00**	**71.34**	**100.00**

Table A.1– Normalised abundances of planktonic foraminifera identified in Episkopeio-Arediou, Mesaoria Plain, Central Cyprus. Note: Red boxes indicate foraminifera with abundances ≥10%, yellow boxes indicate foraminifera with abundances ≥2%

	2.5 m		2.0 m		1.5 m		1.0 m		0.5 m	
	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage
Benthonic Foraminifera										
Astigerinata mamilla	0.00	0.00	3.27	3.15	5.11	4.57	1.79	1.48	12.67	11.65
Cibicides pachydermus	1.29	3.04	6.54	6.29	17.88	15.99	22.05	18.22	12.67	11.65
Cassidulina carinata	1.93	4.55	2.62	2.52	6.39	5.72	3.58	2.96	7.33	6.74
Bolivina spathulata	1.29	3.04	2.62	2.52	2.55	2.28	4.17	3.45	5.33	4.90
Gyroidina orbicularis	2.58	6.08	2.62	2.52	6.39	5.72	4.77	3.94	4.67	4.29
Hyalinea balthica	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.62
Uvigerina peregrina	0.00	0.00	0.65	0.63	0.00	0.00	0.00	0.00	0.67	0.62
Ammonia sp.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.62
Hoeglundina elegans	0.64	1.51	1.31	1.26	0.00	0.00	0.00	0.00	0.67	0.62
Pullenia bulloides	0.00	0.00	0.00	0.00	0.00	0.00	1.19	0.98	0.67	0.62
Elphidium complanatum	0.00	0.00	0.65	0.63	1.28	1.14	0.00	0.00	0.67	0.62
Eggerella bradyi	0.00	0.00	0.65	0.63	0.64	0.57	0.00	0.00	0.67	0.62
Uvigerina mediterranea	0.64	1.51	0.65	0.63	1.92	1.72	7.15	5.91	0.67	0.62
Cruciloculina triangularis	0.00	0.00	0.00	0.00	1.28	1.14	0.00	0.00	0.67	0.62
Siphotextularia concava	0.00	0.00	1.31	1.26	5.11	4.57	1.79	1.48	0.67	0.62
Bolivina albatrossi	0.00	0.00	1.31	1.26	0.00	0.00	0.00	0.00	0.67	0.62
Gyroidina sp.	0.00	0.00	3.27	3.15	0.00	0.00	0.00	0.00	0.67	0.62
Planulina ariminensis	0.00	0.00	1.31	1.26	1.28	1.14	1.79	1.48	0.00	0.00
Bulimina costata	0.00	0.00	0.00	0.00	0.64	0.57	0.00	0.00	0.00	0.00
Hansensica soldanii	0.64	1.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pyrgo murrhina	0.64	1.51	0.65	0.63	0.64	0.57	0.00	0.00	0.00	0.00
Nonionella turgida	0.64	1.51	0.65	0.63	0.00	0.00	0.00	0.00	0.00	0.00
Amphicoryna scalaris	0.64	1.51	0.00	0.00	0.64	0.57	0.00	0.00	0.00	0.00

Table A.2– Normalised abundances of benthonic foraminifera identified in Episkopeio-Arediou, Mesaoria Plain, Central Cyprus. Note: Red boxes indicate foraminifera with abundances ≥10%, yellow boxes indicate foraminifera with abundances ≥2% (table continued on next page)

	2.5 m		2.0 m		1.5 m		1.0 m		0.5 m	
	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage
Benthonic Foraminifera										
Rosalina vilardeboeana	0.64	1.51	0.65	0.63	1.28	1.14	0.00	0.00	0.00	0.00
Globocassidulina subglosa	0.00	0.00	0.65	0.63	0.64	0.57	1.79	1.48	0.00	0.00
Gyroidina umbonata	3.22	7.58	3.93	3.78	3.19	2.85	6.55	5.41	0.00	0.00
Ammonia parkinsona	3.86	9.09	1.96	1.89	7.03	6.29	7.15	5.91	0.00	0.00
Protelphidium phlegeri	0.64	1.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pyrgo luceruda	0.64	1.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Elphidium aculeatum	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.50	0.00	0.00
Lagena striata	0.64	1.51	0.00	0.00	0.00	0.00	0.60	0.50	0.00	0.00
Sigmiolina tenuis	0.00	0.00	0.65	0.63	0.00	0.00	0.60	0.50	0.00	0.00
Haynesina sp.	1.29	3.04	5.89	5.67	4.47	4.00	4.17	3.45	4.67	4.29
Valvulinera bradyana	2.58	6.08	5.24	5.04	8.94	8.00	6.55	5.41	4.67	4.29
Melonis affinis	1.29	3.04	1.31	1.26	0.64	0.57	1.79	1.48	4.67	4.29
Bulimina exilis	3.22	7.58	1.31	1.26	3.19	2.85	2.98	2.46	4.00	3.68
Textularia saggitula	0.64	1.51	3.93	3.78	3.19	2.85	1.79	1.48	4.00	3.68
Melonis bareleanum	1.29	3.04	0.00	0.00	0.00	0.00	1.79	1.48	2.67	2.46
Hanzawaia boueana	0.00	0.00	6.54	6.29	2.55	2.28	1.19	0.98	2.67	2.46
Sphaeroidina bulloides	1.29	3.04	5.24	5.04	0.64	0.57	1.79	1.48	2.67	2.46
Bolivina pseudoplicata	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.67	2.46
Nonion labradocorim	0.00	0.00	1.96	1.89	0.64	0.57	4.17	3.45	2.67	2.46
Melonis bareleeanus	1.93	4.55	3.27	3.15	3.19	2.85	4.77	3.94	2.67	2.46
Globobulimina affinis	1.93	4.55	2.62	2.52	3.83	3.43	4.77	3.94	2.67	2.46
Discorbinella berthaloti	0.64	1.51	1.31	1.26	0.64	0.57	3.58	2.96	2.00	1.84
Trifarina angulosa	0.00	0.00	0.65	0.63	0.00	0.00	1.19	0.98	2.00	1.84

	2.5 m		2.0 m		1.5 m		1.0 m		0.5 m	
	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage
Benthonic Foraminifera										
Lagena hispida	0.64	1.51	1.96	1.89	0.64	0.57	0.00	0.00	1.33	1.22
Pseudoclavulina crustata	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.33	1.22
Rectuvigerina phlegeri	1.29	3.04	0.00	0.00	0.00	0.00	0.00	0.00	1.33	1.22
Bulimina inflata	0.00	0.00	0.65	0.63	0.00	0.00	0.00	0.00	1.33	1.22
Textularia truncata	0.00	0.00	0.65	0.63	1.92	1.72	0.00	0.00	1.33	1.22
Quinqueloculina lamarckiana	0.00	0.00	0.00	0.00	0.64	0.57	0.60	0.50	1.33	1.22
Uvigerina auberiana	0.00	0.00	1.96	1.89	5.11	4.57	1.79	1.48	1.33	1.22
Elphidium margaritaceum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.62
Melonis pompiliodes	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.62
Cibicides kullenbergi	0.00	0.00	0.65	0.63	0.00	0.00	0.00	0.00	0.67	0.62
Bulimina marginata	0.00	0.00	1.31	1.26	0.00	0.00	0.00	0.00	0.67	0.62
Spiroloculina canaliculata	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.62
Miliolina irregularis	0.00	0.00	0.00	0.00	1.28	1.14	0.60	0.50	0.67	0.62
Lagena hexagona	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.50	0.00	0.00
Siphotexularia curta	0.00	0.00	0.65	0.63	1.92	1.72	0.60	0.50	0.00	0.00
Pyrgo comata	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.50	0.00	0.00
Haynesina depressula	0.00	0.00	3.93	3.78	0.00	0.00	1.19	0.98	0.00	0.00
Cancris ariculus	0.00	0.00	0.00	0.00	0.00	0.00	1.19	0.98	0.00	0.00
Neoconorbina terquemi	1.29	3.04	1.31	1.26	0.64	0.57	1.19	0.98	0.00	0.00
Sigmiolina distorta	0.00	0.00	1.31	1.26	0.00	0.00	0.60	0.50	0.00	0.00
Bulimina aculeata	0.00	0.00	0.65	0.63	1.92	1.72	1.79	1.48	0.00	0.00

Table A.2 continued – Normalised abundances of benthonic foraminifera identified in Episkopeio-Arediou, Mesaoria Plain, Central Cyprus. Note: Red boxes indicate foraminifera with abundances ≥10%, yellow boxes indicate foraminifera with abundances ≥2%

	2.5 m		2.0 m		1.5 m		1.0 m		0.5 m	
	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage
Benthonic Foraminifera										
Cibicides westerlorfti	0.00	0.00	0.00	0.00	0.00	0.00	1.19	0.98	0.00	0.00
Rutherfordoides rotundiformis	0.00	0.00	2.62	2.52	0.00	0.00	0.00	0.00	0.00	0.00
Bolivina capitata	0.00	0.00	1.96	1.89	0.00	0.00	0.00	0.00	0.00	0.00
Tretomphalus bulloides	0.00	0.00	0.65	0.63	0.00	0.00	0.00	0.00	0.00	0.00
Ammolagena clavata	0.00	0.00	0.65	0.63	0.00	0.00	0.00	0.00	0.00	0.00
Milliolinella circularis	0.00	0.00	0.65	0.63	0.00	0.00	0.00	0.00	0.00	0.00
Lagena sulcata	0.00	0.00	0.65	0.63	0.64	0.57	0.00	0.00	0.00	0.00
Cassidulina crassa	0.64	1.51	0.65	0.63	0.00	0.00	0.00	0.00	0.00	0.00
Quinqueloculina seminula	0.00	0.00	0.00	0.00	0.64	0.57	0.60	0.50	0.00	0.00
Bolivina seminuda	0.00	0.00	0.00	0.00	0.64	0.57	0.60	0.50	0.00	0.00
Articulina tubulosa	0.00	0.00	1.96	1.89	0.00	0.00	0.00	0.00	0.00	0.00
Plandiscorbis rarescens	1.29	3.04	1.96	1.89	0.00	0.00	0.00	0.00	0.00	0.00
Bolivina alata	0.64	1.51	0.00	0.00	0.00	0.00	1.79	1.48	0.00	0.00
TOTAL	**42.46**	**100.01**	**103.97**	**100.01**	**111.80**	**100.00**	**121.03**	**100.01**	**108.74**	**100.06**

Table A.2 continued – Normalised abundances of benthonic foraminifera identified in Episkopeio-Arediou, Mesaoria Plain, Central Cyprus. Note: Red boxes indicate foraminifera with abundances ≥10%, yellow boxes indicate foraminifera with abundances ≥2%

	5.0 m		4.0 m		3.0 m		2.0 m		1.0 m	
	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage
Planktonic Foraminifera										
Globigerina cariacoensis	0.00	0.00	0.00	0.00	4.57	12.50	5.00	3.70	4.64	10.00
Globigerinoides aff. sacculifer	337.14	57.28	2.42	2.50	1.52	4.16	15.00	11.11	0.00	0.00
Globigerina bulloides	57.14	9.71	55.76	57.51	13.71	37.49	45.00	33.33	9.28	20.00
Globorotalia inflata	0.00	0.00	2.42	2.50	0.00	0.00	20.00	14.81	4.64	10.00
Globorotalia inflata - type 2	0.00	0.00	2.42	2.50	0.00	0.00	0.00	0.00	4.64	10.00
Globorotalia inflata - type 3	0.00	0.00	0.00	0.00	6.10	16.68	0.00	0.00	9.28	20.00
Globorotalia inflata - type 4	5.71	0.97	0.00	0.00	0.00	0.00	0.00	0.00	4.64	10.00
Globoturborotalinid (aff. globoturborotalia)	114.29	19.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Globigerinoides sacculifer	34.29	5.83	2.42	2.50	6.10	16.68	35.00	25.93	9.28	20.00
Orbulina universa	40.00	6.80	31.52	32.51	4.57	12.50	15.00	11.11	0.00	0.00
TOTAL	**588.57**	**100.00**	**96.96**	**100.00**	**36.57**	**100.00**	**135.00**	**100.00**	**46.40**	**100.00**

Table A.3 – Normalised abundances of planktonic foraminifera identified in Vasiliko Quarry, Southern Cyprus. Note: Red boxes indicate foraminifera with abundances ≥10%, yellow boxes indicate foraminifera with abundances ≥2%

	5.0 m		4.0 m		3.0 m		2.0 m		1.0 m	
	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage
Benthonic Foraminifera										
Ammodiscus planorbis	5.71	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ammonia aff. beccarii	68.57	4.82	33.94	15.91	35.05	14.11	10.00	1.83	51.01	11.46
Amphycoryna scalaris	5.71	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bulimina aculeata	85.71	6.02	9.70	4.55	21.33	8.59	140.00	25.69	64.93	14.58
Dentaline flintii	0.00	0.00	4.85	2.27	0.00	0.00	0.00	0.00	0.00	0.00
Cibicides sp.	45.71	3.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Disconorbis bulbis	34.29	2.41	9.70	4.55	1.52	0.61	0.00	0.00	9.28	2.08
Eggerella bradyi	34.29	2.41	0.00	0.00	10.67	4.30	20.00	3.67	18.55	4.17
Elphidium sp.	22.86	1.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Globobulimina affinis	5.71	0.40	12.12	5.68	6.10	2.46	5.00	0.92	0.00	0.00
Gyroidinoides lamarckiana	120.00	8.43	21.82	10.23	15.24	6.14	25.00	4.59	4.64	1.04
Neoconorbina terquemi	360.00	25.30	9.70	4.55	39.62	15.95	85.00	15.60	83.48	18.75
Hyalinea balthica	22.86	1.61	12.12	5.68	7.62	3.07	10.00	1.83	23.19	5.21
Lagena hexagona	28.57	2.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lenticulinid (aff. Lenticulina orbicularis)	0.00	0.00	2.42	1.13	0.00	0.00	0.00	0.00	0.00	0.00

Table A.4 – Normalised abundances of benthonic foraminifera identified in Vasiliko Quarry, Southern Cyprus. Note: Red boxes indicate foraminifera with abundances ≥10%, yellow boxes indicate foraminifera with abundances ≥2%

	5.0 m		4.0 m		3.0 m		2.0 m		1.0 m	
	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage
Benthonic Foraminifera										
Lenticulinid (aff. Lenticulina gibba)	0.00	0.00	2.42	1.13	4.57	1.84	10.00	1.83	0.00	0.00
Melonis bareleeanus	45.71	3.21	21.82	10.23	9.14	3.68	45.00	8.26	13.91	3.12
Nonion sp.	22.86	1.61	0.00	0.00	4.57	1.84	15.00	2.75	0.00	0.00
Nutallinid (aff. nuttalides)	11.43	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Palliolatella orbignyana	17.14	1.20	0.00	0.00	1.52	0.61	5.00	0.92	0.00	0.00
Planorbulina mediterranensis	28.57	2.01	0.00	0.00	1.52	0.61	0.00	0.00	0.00	0.00
Portatrochammina	5.71	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Quinqueloculina limbata	17.14	1.20	4.85	2.27	1.52	0.61	15.00	2.75	18.55	4.17
Quinqueloculina aff. stelligera	0.00	0.00	7.27	3.41	0.00	0.00	0.00	0.00	9.28	2.08
Siphonina reticulata	40.00	2.81	2.42	1.13	0.00	0.00	10.00	1.83	4.64	1.04
Recurvoides sp.	17.14	1.20	0.00	0.00	3.05	1.23	0.00	0.00	4.64	1.04
Reusella spinulosa	80.00	5.62	0.00	0.00	1.52	0.61	15.00	2.75	13.91	3.12
Rosalina sp.	0.00	0.00	9.70	4.55	6.10	2.46	10.00	1.83	27.83	6.25
Brizalina spathulata	194.29	13.66	19.39	9.09	54.86	22.09	85.00	15.60	32.46	7.29
Brizalina striata	28.57	2.01	4.85	2.27	4.57	1.84	10.00	1.83	9.28	2.08
Cassidulina aff. laevigata	34.29	2.41	9.70	4.55	12.19	4.91	10.00	1.83	41.74	9.37
Uvigerina mediterranea	40.00	2.81	14.55	6.82	6.10	2.46	20.00	3.67	13.91	3.12
TOTAL	**1422.84**	**100.00**	**213.34**	**100.00**	**248.38**	**100.00**	**545.00**	**100.00**	**445.23**	**100.00**

Table A.4 continued – Normalised abundances of benthonic foraminifera identified in Vasiliko Quarry, Southern Cyprus. Note: Red boxes indicate foraminifera with abundances ≥10%, yellow boxes indicate foraminifera with abundances ≥2%

Appendix B

Foraminiferal species identified in reconnaissance samples

	Species	Abundance (%)
PLANKTONIC	*Globigerina bulloides*	2.2
	Globigerina cf. siphonifera	2.2
	Globigerinoides ruber	8.7
	Globigerinoides sacculifer	10.9
	Globorotalia cf. mediterranea	2.2
	Globigerina rubescens	6.5
	Globigerinoides tenellus	4.3
	Neogloboquadrina dutertrei	2.2
	Neogloboquadrina pachyderma	2.2
	Orbulina universa	50.0
	Praeorbulina transitoria	2.2
	Species C	2.2
	Species D	4.3
BENTHONIC	*Biloculinella depressa*	1.7
	Cibicides kullenbergi	5.0
	Cibicides pachydermus	3.3
	Cibicides sp.	10.0
	Cymbaloporetta sp.	3.3
	Discorbinella berthaloti	1.7
	Globobulimina affinis	10.0
	Gyroidinoides lamarckiana	1.7
	Gyroidinoides cf. soldanii	3.3
	Gyroidinoides sp.	8.3
	Lobatula cf. lobatula	3.3
	Melonis affinis	3.3
	Melonis barleeanum	1.7
	Nonionella turgida	1.7
	Nuttallinid cf. nuttalides	3.3
	Planulina ariminensis	3.3
	Pullenia sp.	1.7
	Pyrgo oblonga	1.7
	Reophax sp. 1	1.7
	Sigmoilopsis schlumbergeri	1.7
	Siphonaperta cf. dilitata	1.7
	Species A	8.3
	Species B	1.7
	Sphaeroidina bulloides	5.0
	Spiroloculina canaliculata	1.7
	Tretomphalus bulloides ?	1.7
	Uvigerina peregrina	8.3

Table B.1 – Foraminiferal species identified in Pissouri. Key planktonic species identified in Khirokitia included *Orbulina Universa*, *Globorotalia inflata* and *Sphaeroidinellopsis Seminulina*.

Appendix C

Diagnostic features of benthic foraminiferal species ≥ 2% abundance

The following descriptions are based upon Loeblich & Tappan (1988) and Cimerman & Langer (1991).

Ammonia Parkinsona: planoconvex and trochospiral. Umbilical side displays a well developed knob. On the spiral side sutures are backward curved and slightly thickened, on the umbilical side they are deeply with incised interlocular spaces. 8-9 chambers (umbilical), ~2.5 whorls (spiral). Flattened umbilical side, evolute spiral side and interiomarginal aperture.

Astigerinata mamilla: planoconvex and trochospiral. Sutures are curved, imperforate and slightly thickened on spiral side, weakly depressed, curved to sinuate on umbilical side. 5-6 chambers, 3-4 whorls. Involute umbilical side, evolute spiral side and interiomarginal aperture. Crescentic chambers increase in size and on the umbilical side there are several large pores present.

Bulimina aculeata: small triserial test with inflated, broadly rounded chambers, which rapidly increase in size as added and overlap in consecutive coils. Depressed and oblique sutures. Several distinctive long pseudospines occur on lower part of the shell. Exhibits a (buliminid loop) aperture with a toothplate.

Brizalina spathulata: biserial test with weakly depressed sutures and up to 32 chambers. Densely perforate wall at outer chamber margin and near the sutures with several weakly developed longitudinal striae on lower part of the shell. Elongate interiomarginal loop aperture bordered by a rim and with a toothplate.

Brizalina striata: biserial test that tapers and elongates with a subrounded to acutely angled periphery. 16-21 chambers (adult) with weakly depressed and oblique sutures, densely perforate wall and several longitudinal and imperforate costae. Elongate interiomarginal loop aperture surrounded by a bordering lip and with a toothplate.

Bolivina spathulata: biserial test and acute periphery with weakly depressed sutures. Densely perforate wall at outer chamber margin and near the sutures. Up to 32 chambers and several weakly developed longitudinal striae on lower part of the shell. Elongate interiomarginal loop aperture, bordered by a rim and with a toothplate.

Eggerella bradyi: subconical test and finely agglutinated wall. Aperture is a low slit near the base of the apertural face, bordered by a narrow lip. 3 chambers per whorl.

Gyroidina orbicularis: trochospiral with an evolute spiral side, flattened or slightly convex chambers in 2.5 to 3 gradually enlarging whorls. Sutures are curved back to the periphery. The umbilical side is strongly convex and involute with curved sutures, nearly radial and closed umbilicus. Periphery bluntly angled and coarsely perforate. Interiomarginal apertural slit extends nearly to the periphery and halfway to the umbilicus.

Gyroidinoides lamarckiana: trochospiral and nearly planoconvex test. Spiral side evolute and flattened with slightly elevated proloculus. ~ 3 whorls and 5-6 chambers in the final whorl, slowly increasing in size as added. Sutures are depressed and nearly straight. Umbilical side sutures are radial. The surface is smooth and densely perforate and the interiomarginal aperture is bordered by thickened rim.

Hyalinea balthica: trochospiral test, flat, 10-12 chambers in final whorl with curved limbate sutures. The periphery has a distinct truncate carina and the aperture is a low equatorial arch bordered by a rim, which continues into a spiral aperture with a lip.

Melonis barleeanus: planispiral test, involute, symmetrical, biumbilicate with rounded, slightly appressed, peripheral margin. 9-10 chambers in final whorl, gradually increasing in length, breadth and thickness with radial and slightly curved sutures and densely perforate wall. The aperture is an interiomarginal and equatorial slit bordered by a rim.

Nonion labradocorim: trochospiral (early stage), nearly planispiral & involute (later stage) with chambers enlarging rapidly as added. Inflated basal lobe on umbilical side, periphery is subangular to rounded, finely perforate, smooth surface other than pustules at umbilical ends of chambers. The aperture is an interiomarginal and equatorial arch.

Quinqueloculina limbata: porcelanous and imperforate test, subelliptical (lateral view), subtriangular (apertural view) with rounded periphery, chambers one-half coil in length arranged in a quinqueloculine pattern (5 chambers visible from exterior). Distinctive longitudinally arranged costae are present on the surface (predominantly on the periphery). A circular aperture bordered by collarlike peristomal rim, is slightly produced on a short neck and with a bifid tooth.

Reusella spinulosa: triserial test, acutely angled and triangular, with numerous backward projecting short pseudospines along the carinate margins and along sutures. Chambers gradually increase in size as added and the sutures are distinct and thickened. Pores are mainly located along chamber-margins, the triangular sides of tests are flattened and an interiomarginal slit like aperture with an internal toothplate is evident.

Rutherfordoides rotundiformis: elongate, subfusiform test. Chambers are biserially arranged and strongly oblique, broad and low on the dorsal side, whilst strongly overlapping and inflated on the ventral side. Sutures are oblique and flush to slightly depressed. The test surface is finely perforate, smooth and polished and the aperture is an elongate, subterminal loop, which extends up the face of final chamber.

Sphaeroidina bulloides: subglobular test, variable coiling, very finely perforate with smooth surface. Aperture is a crescentic opening near base of the chamber bordered by a narrow lip, may have a simple flaplike or bifid tooth.

Siphonina reticulata: trochospiral, subrounded (outline), biconvex (peripheral view), spiral side evolute with oblique sutures, umbilical side involute. Chambers are subtriangular in outline. Keeled periphery, weakly fimbriated and perforate with an equatorial, subrounded aperture situated on a short neck and bordered by phialine lip. The inner margins of chambers are perforate.

Textularia saggitula: elongate test, laterally compressed with acute periphery, thickest in the median line, planispiral (3-4 chambers) initial stage. Chambers gradually enlargen as added and the aperture is a low slit at the base of the final chamber. Sutures are depressed and slightly curved whilst the peripheral wall is penetrated by straight +/ branching parapores.

Uvigerina mediterranea: elongate, triserial test. Chambers are inflated and rapidly increase in size as added. Sutures are distinct, depressed and somewhat oblique. Finely perforate wall, surface exhibits sharp, longitudinal costae which are discontinuous at sutures. The aperture is terminal, produced on a short neck with a hemicylindrical toothplate.

Valvulinera bradyana: trochospiral test, subrounded periphery, spiral side advolute, slightly convex with weakly depressed initial stage. Umbilical side is involute with depressed umbilicus. Sutures are gently curved backwards on spiral side, radial and slightly curved on umbilical side. Smooth and densely perforate surface with an interiomarginal, umbilical to extraumbilical arch aperture, with a large flap covering the umbilicus.

Appendix D

Rainfall data for Cyprus

Locality	Area in relation to the Troodos Mountains	Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Polis Chyrsochous	Southwest	95.3	70.1	61.2	26.9	13.2	1.7	0.8	0.7	2.2	38.0	64.3	99.7
Pafos (airport)	Southwest	94.0	69.0	49.0	24.0	10.0	0.7	0.2	0.2	1.7	31.0	52.0	98.0
Prodromos	Troodos Mountains	192.9	145.3	120.4	53.6	36.9	20.2	14.0	13.0	10.0	47.1	83.7	182.3
Saittas	Southern Troodos foothills	145.3	111.2	83.3	47.8	36.4	10.5	8.1	14.5	10.3	41.3	67.1	138.5
Lemesos	South	96.1	76.3	49.1	23.5	7.5	2.7	2.5	0.5	1.1	25.6	48.2	102.0
Athalassa	North	48.0	47.0	37.0	22.0	22.0	7.0	1.0	7.0	6.0	22.0	31.0	58.0
Paralimni	East	70.0	62.0	35.0	7.5	2.5	0.5	0.3	1.2	25.0	22.0	45.0	87.0

Table D.1 – Monthly precipitation records from 1961-1990 (mm)

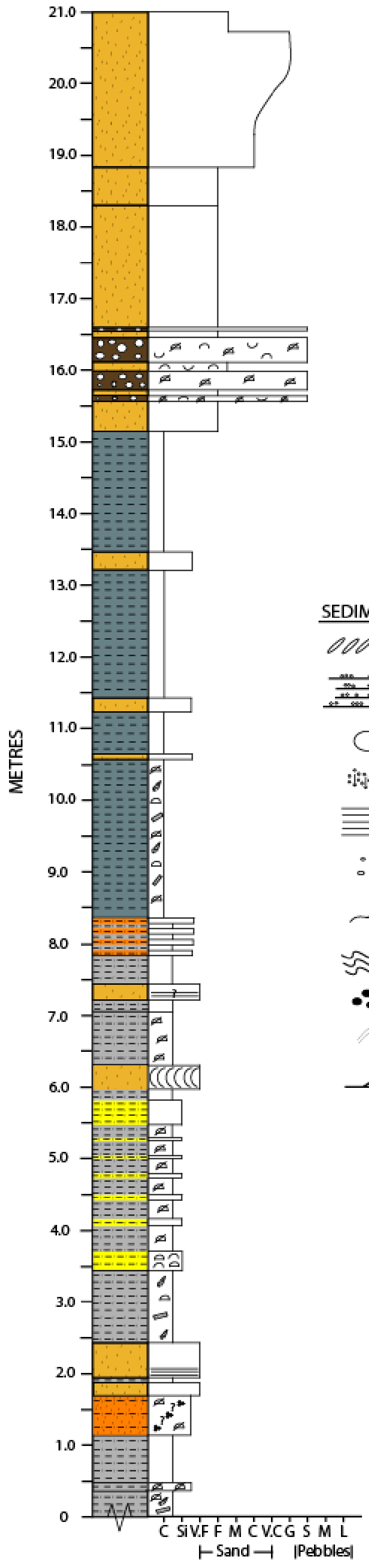
Locality	Area in relation to the Troodos Mountains	Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Polis Chyrsochous	Southwest	79.9	67.1	37.6	24.7	7.2	1.5	0.2	0.0	4.4	21.8	55.3	94.4
Pafos (airport)	Southwest	80.2	64.2	34.4	18.7	5.3	1.6	0.3	0.0	3.8	18.0	66.4	93.9
Prodromos	Troodos Mountains	133.4	123.6	82.3	56.9	26.0	40.0	12.1	10.0	9.5	24.0	102.5	169.7
Saittas	Southern Troodos foothills	117.6	89.0	70.3	38.4	20.1	27.2	4.9	10.3	11.7	25.7	93.9	144.0
Lemesos	South	86.7	66.9	35.8	18.4	5.1	1.4	0.0	0.0	2.9	13.1	77.5	99.7
Athalassa	North	54.7	41.6	28.3	19.9	23.5	17.6	5.8	1.3	11.7	17.4	54.6	65.8
Paralimni	East	87.6	48.2	27.5	20.3	8.0	0.9	0.1	1.2	4.1	16.2	53.5	101.3

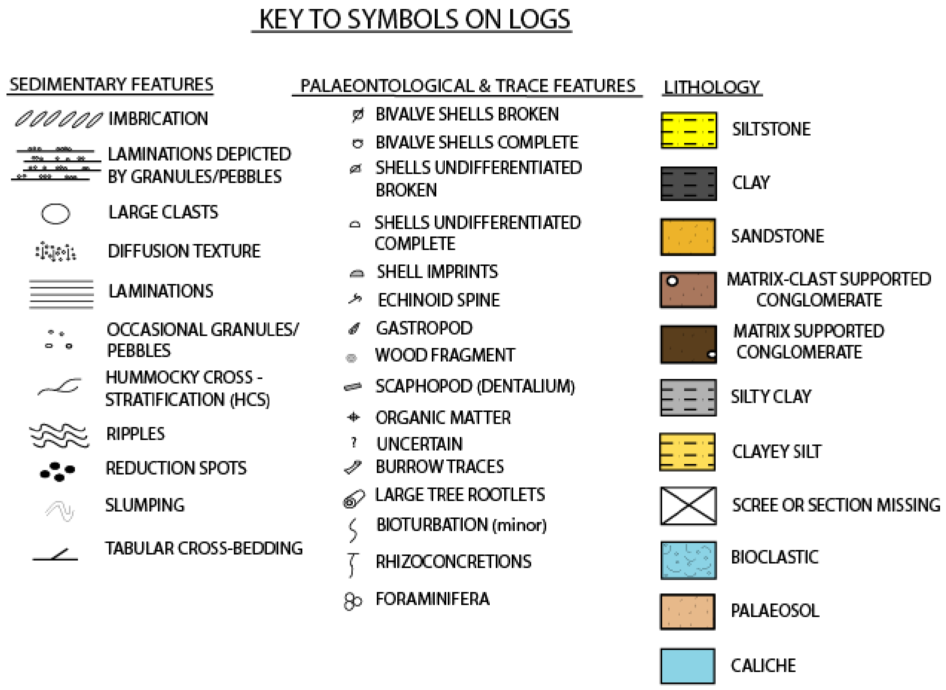
Table D.2 – Mean monthly precipitation records from 1991-2005 (mm)

Data is from the Cyprus Geological Survey Meteorological Service (2009).

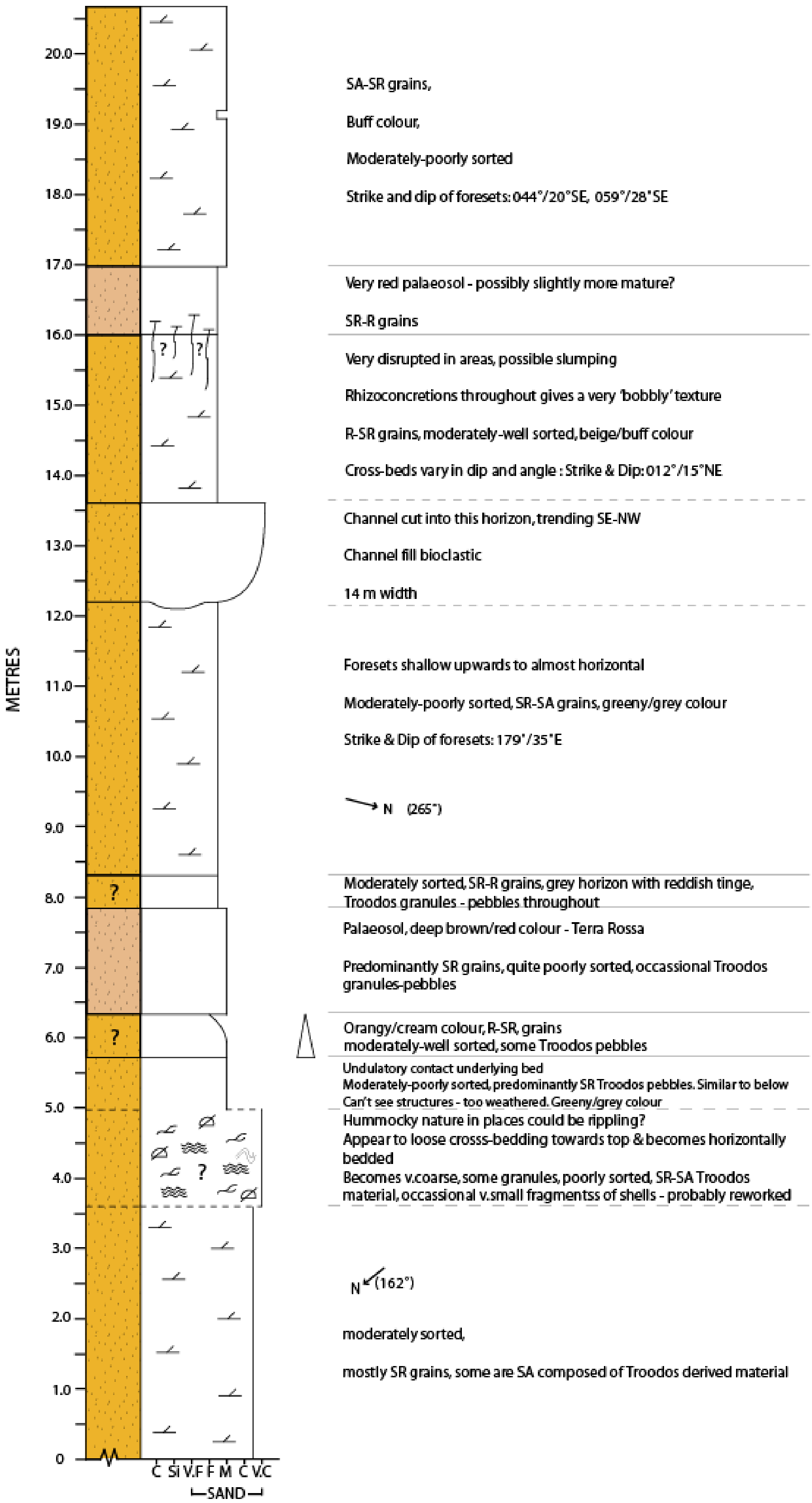
Appendix E

Graphic logs of fan deltas in the Pissouri area

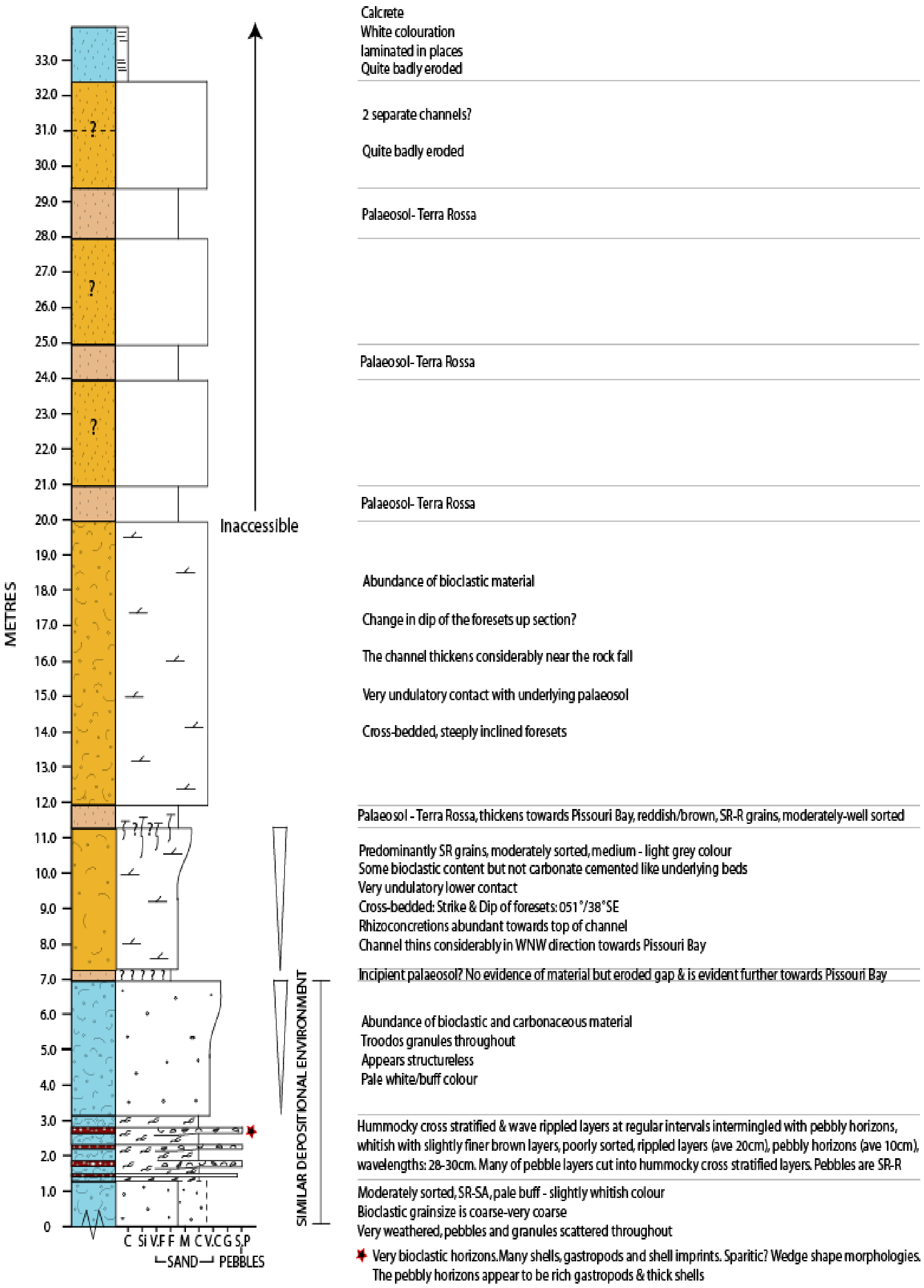




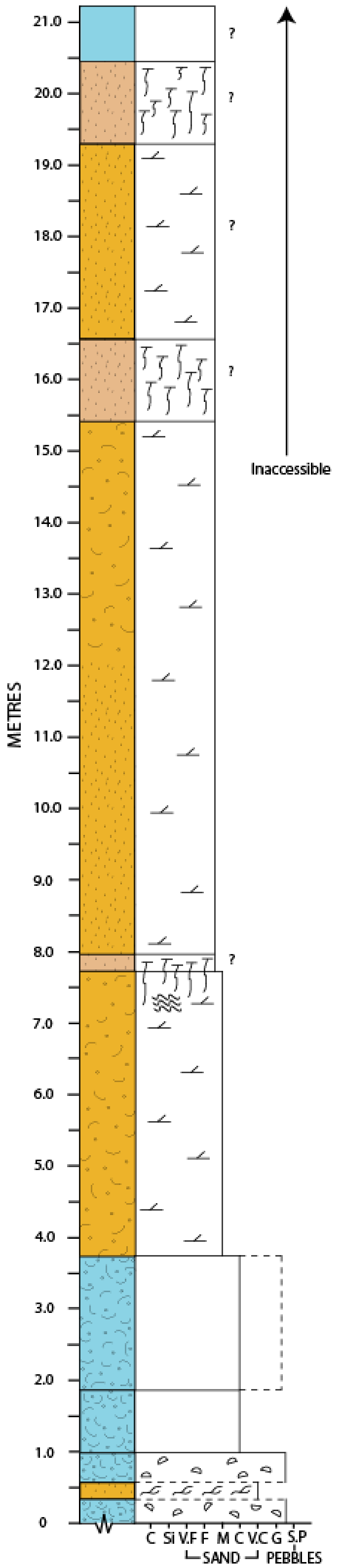
Log E.1 – Pissouri ‘old’ village, (34˚40.399N 32˚42.07E), Locality 2, Fig. 3.2



Log E.2 – Pissouri 'old' village, (34˚40.301N 32˚41.887E), Locality 2, Fig. 3.2. 253 m.a.s.l. Note: ~40m of scree lie between the logged section and the underlying Nicosia Formation



Log E.3 – Pissouri beach section, (34˚38.833N 32˚44.596E), Locality 1, Fig. 3.2



Calcrete

Palaeosol - Terra Rossa

Attains thickeneses up to ~5m thick

Fallen blocks on beach suggest many root traces throughout the bed

Quite weathered although cross-bedding in places

Very steeply inclined foresets, quite crudely depicted

Top of the horizon covered in layer of caliche?

NOTE: On top of this channel (round headland towards Melounda Beach) is conglomeratic alluvial fan material (4m 80cm thick). Much later deposit incised into the succession?

This palaeosol is only identifiable on the headland
Thickens in NNE direction
Many large rhizoconcretions throughout

Shallower dip of foresets compared to underlying channel, foresets are siliciclastic

Strike & Dip of foresets: 171˚/16˚E

Bed pinches out to the NW towards Pissouri Bay

Relatively sharp underlying contact & upper contact

Predominantly SR grains, moderately well sorted

Round the corner towards Melounda Beach sediment is very poorly sorted, medium up to coarse grained and appears more cemented. Looks like a combination between the basal bioclastic layer & underlying siliciclastic channel

Orangy/brown colour

Incipient palaeosol? SR-SA grains, moderately sorted, reddish brown colour (Terra Rossa) (1m thick in places)

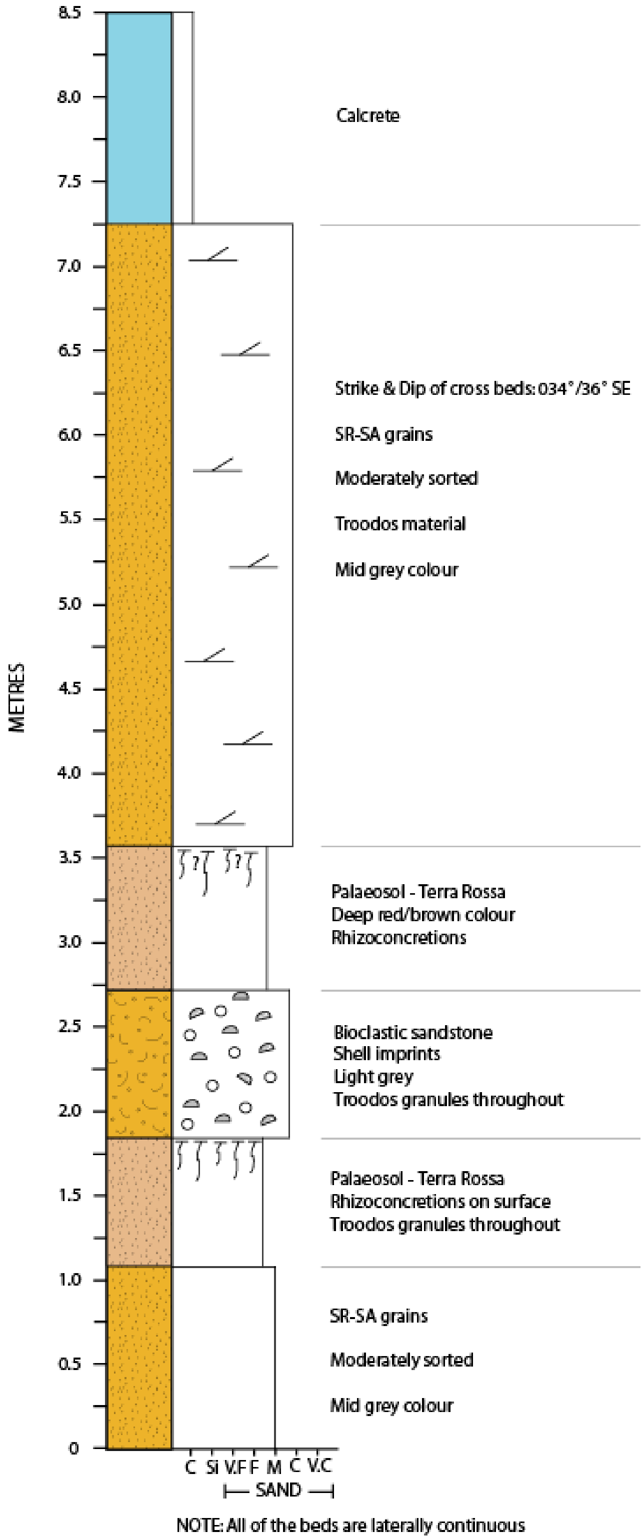
Note: Moved around coast towards Melounda Beach, following the dip of the bed
Foresets dip in different directions. Strike & Dip of foresets: 048˚/26˚SE, 047˚/28˚SE, 057˚/31˚SE, 027˚/29˚ESE (as move round corner) 132˚/18NE˚ (right on the corner), 128˚/17˚SW, 150˚/26˚SW (all in 3D - true dips)
Still bioclastic but finer grained compared to underlying facies. Been reworked a lot?
No rhizoconcretions on main section of beach
Bed thickens to SE
Pale grey colour - maybe due to weathering
As move round to SE rhizoconcretions become more abundant (thicker palaeosol horizon over the top of the bed)
X-beds are closer together & appear more laminated on headland
Tree trunks in layer - probably fairly recent? (calcretised)
Rippling in area disturbed by rhizoconcretions, wavelengths: 39cm/47cm/44cm

Very weathered appearance - therefore appears structureless
Bioclastic
Troodos pebbles to granules throughout
Thickens to the ESE
May be 2/3 beds here, picked out by the weathering profile

Beds are 1-2cm thick, alternations between coarser & finer beds.
Contacts relatively sharp but quite weathered.
Horizontally bedded bioclastic bed.

Bioclastic bed composed of rounded small pebbles & granular layers (Troodos derived) interspersed at regular intervals with pebbly horizons depicted by storm beds. Bioclastic bed contains marine bivalve shells & possible scaphopods in carbonate matrix (little channels?) Storm horizons contain a lack of pebbles & smaller bioclasts, no obvious shells. Appears to be an overall crude fining upward pebbly bioclastic layers. Herring-bone cross bedding also present suggesting a tidal influence. Relatively sharp contacts between storm beds & pebbly layers. Pale cream colour. Wavelenghts of swales: 55 cm/45cm/45cm

Log E.4 – Pissouri beach section, (34˚33.798N 32˚44.634E), Locality 1, Fig. 3.2



Log E.5– Pissouri beach, upper part of the cliff face - poor accessibility. (34˚38.909N 32˚44.269E), Locality 1, Fig. 3.2

Appendix F

Connection between sea level, raised beach and alluvial fan terraces

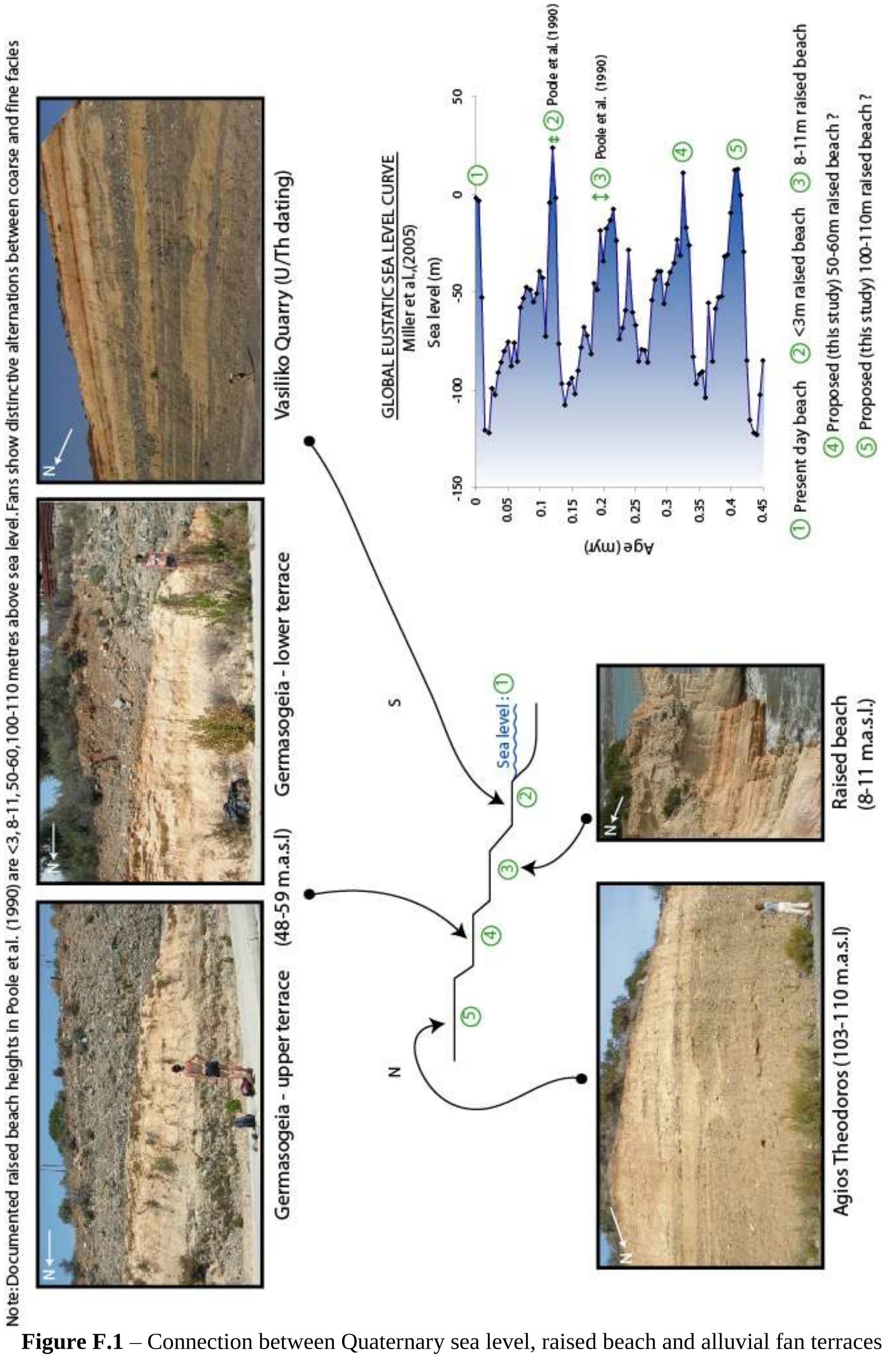


Figure F.1 – Connection between Quaternary sea level, raised beach and alluvial fan terraces

Appendix G

Additional thin section images of facies within the Pissouri Fan Delta

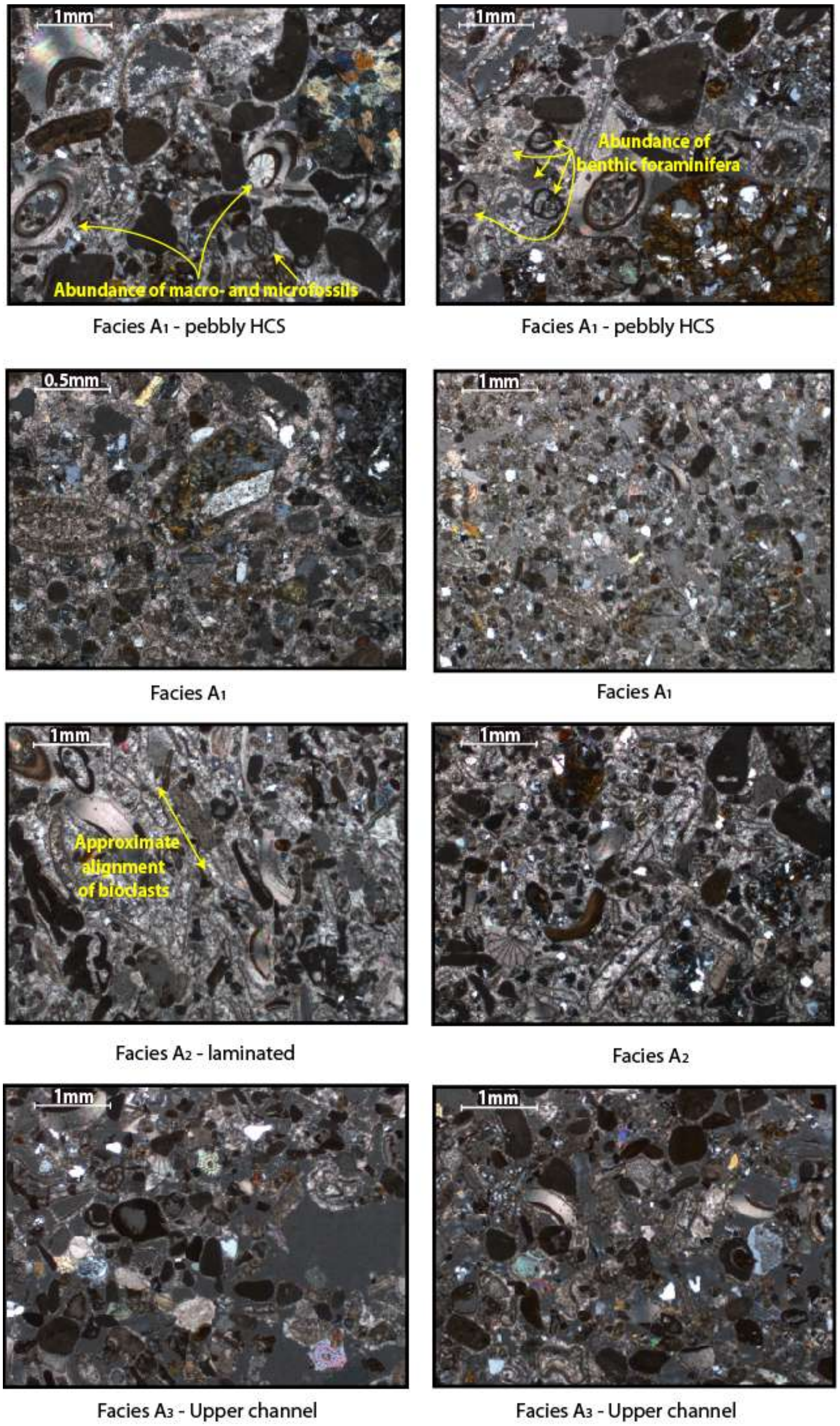
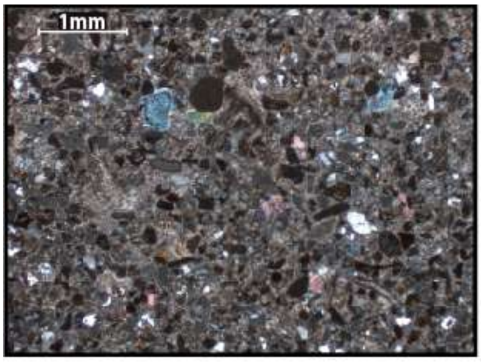
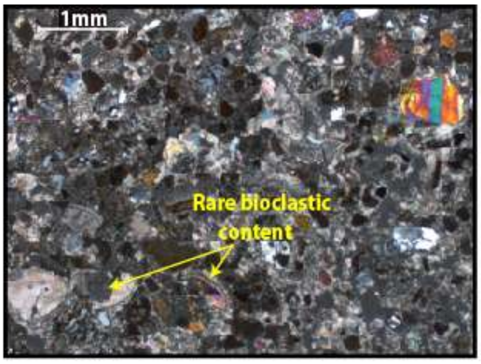


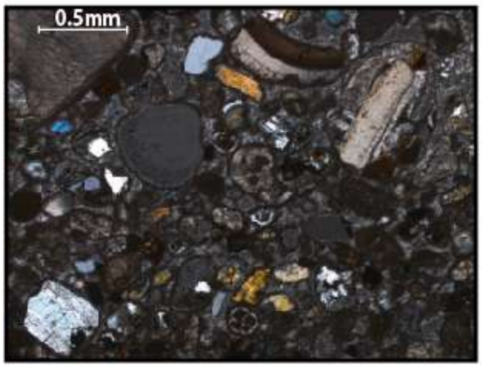
Figure G.1 – Additional thin sections of the Pissouri Fan Delta facies



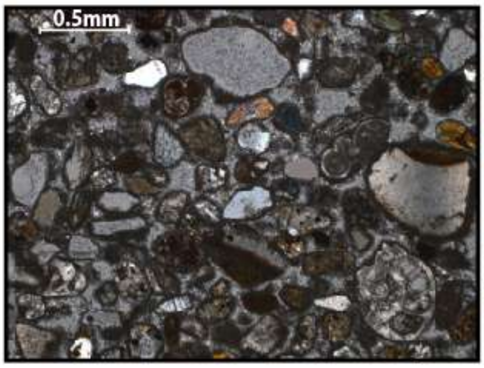
Facies A_3 - Lower channel



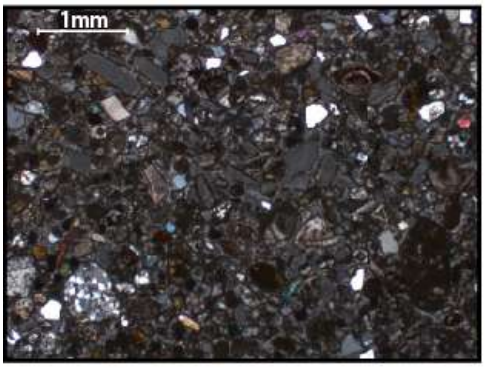
Facies B_1



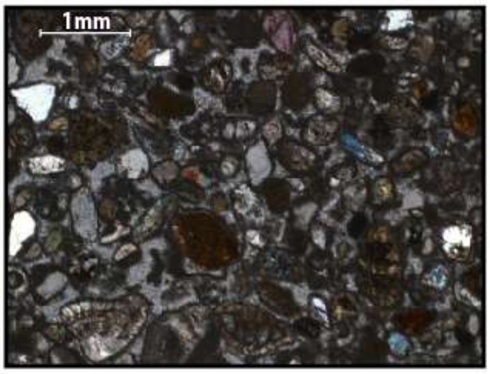
Facies B_2



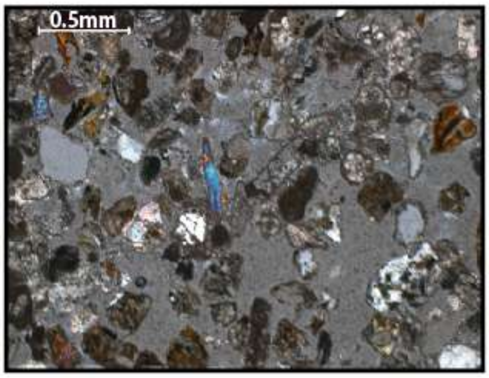
Facies B_2



Facies B_2



Facies B_2



Facies B_3

Figure G.1 continued – Additional thin sections of the Pissouri Fan Delta facies

Appendix H

Explanation of input parameters for palaeoflow calculations in Chapter 4 and associated formulae

Assessment of palaeoshear/palaeoflow velocity: Palaeoshear velocity was determined from the graph devised by Walker in Harms et al. (1975). By plotting the largest size of bedload that can be rolled versus the largest size of sand/granules that can be suspended by the same flow a palaeoshear velocity can be obtained.

Assessment of grain size: Grain size measurements of the conglomerates were obtained by measurement of the long axis (*a*-axis) orientations of clasts of at least 20 clasts per horizon, per log location.

Assessment of channel depth: Channel depth was assessed using large-scale planar cross-stratification (Jones & Frostick, 2008) or thickness of lateral accretion deposits (Miall, 1996), this gives a reasonably reliable approximation of channel depth. Where this was not possible the thickness of the channel fill deposit was used, giving a maximum channel depth.

Assessment of palaeoslopes: To determine a direct measurement of palaeoslope good exposure and a long cross-sectional profile are required. Accurate measurement of palaeoslope for the Vasiliko fan succession was therefore not determinable in the field. The equation devised by Paola & Mohrig (1996) was used to ascertain the palaeoslopes of the channels within the fan succession.

Assessment of maximum clast size: The 90th percentile (D_{90}) was calculated. The absolute maximum clast size was not used as this would be an over representation of the clast size and would be of little statistical use (Jones & Frostick, 2008).

Formulae:

Formula for calculation of palaeoslope estimate: Sest = 0.094(D50)/h
Formula for calculation of Specific stream power: W = ρghSu
Formula for calculation of Froude Number: F = U/√gh

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